RESPONSES OF GRAIN SORGHUM TO PROFILE AND TEMPORAL DYNAMICS OF SOIL WATER IN A SEMI-ARID ENVIRONMENT

A Dissertation

by

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ABSTRACT

Development of efficient irrigation strategies is a priority for producers faced with water shortages. Managed deficit irrigation attempts to optimize water use efficiency (WUE) by synchronizing crop water use with reproductive stages. Soil water use and yield of grain sorghum [*Sorghum bicolor* (L.) Moench], on a Torrertic Paleustoll in the Texas High Plains, USA, were evaluated during the 2010 to 2012 growing seasons under three sprinkler irrigation strategies: full (FI), deficit (DI), and managed deficit irrigation (MDI). Soil water contents were measured weekly at 0.20-m intervals from 0.10 to 2.30 m depth using a neutron moisture gage. Irrigation for the FI treatment was scheduled when root zone water (0 to 1.6 m) was depleted to 50% of the potential plant available water (PPAW). The DI treatment was irrigated at 50% of FI. The MDI treatment was irrigated at 75% of FI between growing point differentiation and half-bloom, 50% of FI after half-bloom, and less than DI prior to growing point differentiation.

Fully irrigated sorghum grain yields averaged 3.7 Mg ha^{-1} greater ($p < 0.001$) than deficit irrigated sorghum in all years. Seasonal crop water use under MDI averaged 29 mm greater than DI. Concomitant with increased water use principally during the reproductive period, MDI yields averaged 1.6 Mg ha^{-1} greater than DI, which was significant in 2010 and 2012 ($p \leq 0.006$). The WUE of FI sorghum was significantly greater than MDI in 2012 ($p = 0.003$) and DI in 2010 and 2012 ($p \leq 0.001$). In 2011, crop water uptake was restricted to above 0.6 m when water contents deeper in the profile were less than 42% PPAW. In 2010 and 2012, seasonal crop water uptake in the profile below 1.0 m was small (<14 mm) and did not appreciably increase in response to imposed soil water deficits. The rooting zone for evaluating plant water status and hence irrigation scheduling depended on initial profile water contents and possibly root density deeper in the profile. Results suggest that WUE's of grain sorghum are not compromised under MDI compared with FI in most cropping seasons.

Dedicated to my children:

Garrett, Peyton, and Avery

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NOMENCLATURE

DI	Deficit Irrigation
ET	Crop Evapotranspiration
$\boldsymbol{ET_c}$	FAO-56 Predicted Crop Evapotranspiration
$\boldsymbol{ET_0}$	Potential Evapotranspiration
FI	Full Irrigation
$\boldsymbol{GDD_c}$	Growing Degree Days (Celsius)
HI	Harvest Index
$\mathbf{K_c}$	FAO-56 Crop Coefficient
MDI	Managed Deficit Irrigation
PPAW	Potential Plant Available Water
SPP	Seed Per Panicle
WUE	Water Use Efficiency

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CHAPTER I

INTRODUCTION AND LITERATURE REVIEW

Crop production for food, feed and fiber is placing greater demands on water resources, especially groundwater because of a growing global population and rising living standards. The global food demand is projected to increase 50% over the next 20 to 25 years, with approximately 80% of the projected increase coming from developing countries including arid and semi-arid regions of sub-Saharan Africa (Dar and Twomlow, 2007) and in regions where water was once relatively plentiful (Deely and Falter, 2000). Irrigated food and feed production accounts for more than 40% of the total food produced globally (Fereres and Soriano, 2007; FAO, 2006); which highlights the importance of irrigated agriculture in stabilizing food production and the need to improve efficiency of water use (FAO, 2006). Although consequences of irrigated food and feed production are often viewed negatively, globally there are appreciable societal benefits from the promotion and adoption of sustainable irrigation practices, such as enhanced food security and improved rural economies. Historically, increases in irrigated acreage were largely responsible for increased crop production (Howell 2006, Rhoades, 1997), but further increases in production from irrigation will be curtailed by aquifer depletion, reduced base flows of rivers, and reallocation of agricultural water to other users. Diminishing availability of water resources will necessitate the adoption of management strategies that attempt to maximize the return per unit water consumed (water use efficiency) rather than the return per unit land area (Evans and Sadler, 2008; Fereres and Soriano, 2007) if production is to be maintained or increased. While improvements in irrigation technology have greatly increased the amount produced per unit irrigation water used, water use efficiency (WUE), advancements in irrigation management strategies likely will provide the most extensive water savings (Garces-Restrepo et al., 2007).

On the Great Plains, irrigation water supplied from the Ogallala Aquifer is becoming less reliable due to declining well capacities, negligible recharge, and increasing energy costs. The Ogallala Aquifer is an unconfined aquifer that underlies 450,000 km^2 of the western Great Plains stretching from South Dakota to Texas. As a result of historically intensive water use from irrigation, the average saturated thickness for the aquifer has declined more than 30.3 meters since the 1940's across much of the High Plains (USGS, 2013). However, the Ogallala Aquifer is also the primary domestic water supply for over 75% of the population in the Great Plains (USGS, 2008). To sustain domestic and industrial requirements, agricultural water use is projected to decrease by up to 34% as a result of ensuing policies to restrict pumping (Wagner, 2012). Future water use will be limited either by restricted pumping or by reduced well capacities. As producers in this region adopt conservation measures driven by limited water supplies and social pressures, management strategies that incorporate low levels of irrigation in contrast to existing irrigation practices could potentially stabilize crop production and an agriculturally driven economy for an extended period (Bordovsky et al., 2011). However, the reduction in regional water use with improved management strategies can only be realized if regional water districts limit the expansion of irrigation so that water savings are not lost to further increases in irrigated acreage.

In semiarid regions such as the Texas High Plains, WUE is considered the standard by which cropping systems and management practices are compared (Hatfield et al., 2001). In these regions, Hatfield et al. (2001) stressed the importance of management practices that account for their associated effects on WUE through consideration of evapotranspiration fluxes, stored soil moisture, and the ability of the plant to extract water from the soil profile all of which are interdependent. While strategies are developed and evaluated to enhance WUE*s* of the crops, it is important to consider that yield responses to irrigation are often location-specific and vary among years (Klocke et al., 2012). A better understanding of soil-root-water interactions in water limited ecosystems is a fundamental step to develop sustainable and efficient irrigation strategies for growers faced with maximizing yield under the constraints of limited water supplies.

Increased knowledge of crop physiological responses to water deficits will assist in management recommendations for irrigation scheduling. Improved WUE under water deficits may be a result of (i) improved application efficiency of irrigation water as a result of less frequent applications and consequently less soil water evaporation, (ii) reductions in transpiration during growth stages that contribute little to grain yield, and (iii) greater use of stored soil water which may be otherwise lost to drainage. Monteith (1986) likewise recommended applying water at critical points where the demand, determined by photosynthesis, exceeds the supply, which is determined by the extension of the root system. The challenge is to develop efficient and sustainable management practices that incorporate improved hybrids while increasing WUE (Hatfield et al., 2001).

Deficit irrigation strategies have the potential to increase agricultural water savings and improve WUE*s* by optimizing the use of irrigation water and precipitation when coupled with drought tolerant crops and by permitting short-term water stress with only marginal decreases in yield and quality. Deficit irrigation may be managed (MDI) whereby applications of water occur at critical growth stages, or unmanaged (DI) and simply based on irrigation applications at a fraction of potential water use by a fully irrigated crop where water stress is not yield limiting. An optimal deficit irrigation strategy should permit crops to more fully utilize pre-plant soil water compared with a fully irrigated crop. A critical component of MDI is minimizing early season soil evaporative losses, which can be achieved by concentrating irrigation during critical growth stages and minimizing pre-plant and early season irrigation events.

Despite economic and social pressures associated with aquifer depletion, pre-plant irrigation is a common practice on the High Plains. Pre-irrigation is often practiced to increase water storage in the profile prior to planting in order to reduce the number of in-season irrigations (especially when well capacities are limited) and improve crop establishment. Greater water storage deeper in the profile prior to planting can increase yield potential of drought tolerant varieties if roots can access this water during critical growth stages (Evans and Sadler, 2008). In agreement, early irrigation work on the

Texas High Plains by Jones and Gaines (1941) stressed the importance of a wet soil profile at planting (Musick and Lamm, 1990). While Musick and Lamm (1990) stated that pre-irrigation often has little effect on grain sorghum yield unless necessary to crop establishment, they concluded that pre-irrigation to fill the profile was more efficient if seasonal irrigation was limited. Howell et al. (2007) demonstrated that deficit irrigated grain sorghum established on a nearly-full soil water profile permitted enhanced soil-water extraction and only marginal declines in yield compared to fully irrigated sorghum. However, frequent and shallow (e.g., $\leq$ 20 mm) sprinkler irrigation applications during the growing season can result in shallow sorghum root development (Myers et al., 1984), which may reduce water uptake deeper in the profile. Lamm et al. (1994) also noted that as irrigation frequency became limited, there was an increase in soil water use from deeper depths of the soil profile. Nevertheless, research in both cotton and grain sorghum has recognized that pre-plant and early season irrigation is 50% less efficient in enhancing yield than water applied during critical growth stages (Bordovsky et al., 2011; Allen and Musick, 1993). Consequently, pre-irrigation can be an inefficient use of a limited water supply (New, 2004). Accordingly, both the timing and amount of irrigation during the growing season are critical to the success of deficit irrigation strategies. Vadez et al. (2013) concluded that research results from many crops grown under deficit conditions suggests that water use should be shifted from the vegetative to the reproductive stage to increase yield under water-limited conditions. Elimination of the least productive irrigations can potentially increase water use efficiency (Hoffman and Martin, 1993), which minimizes early season evaporative losses in favor of crop transpiration.

In semi-arid regions, deficit irrigation often results in soil salinization (Childs and Hanks, 1975). Salinization can occur as salts accumulate following high rates of soil evaporation. However, salinity is of less concern in semi-arid regions with high humidity or winter precipitation because a sufficient supply of fresh water can leach salts from the root zone (English et al., 2002). With lacking fresh water supplies, irrigation water must be applied in excess of *ET* to leach salts and toxic ions from the root zone (Fereres and

Soriano, 2007), which is often not a sustainable practice when irrigation water is of poor quality or limiting.

Sorghum (*Sorghum bicolor* (L.) Moench) is a drought tolerant crop that is suitable for production with deficit irrigation strategies due to its physiological adaptability to short-term water stress. Physiological adaptations in grain sorghum for drought tolerance are associated with the formation of epicuticular wax and osmotic adjustment (Stedudle and Peterson, 1998). Epicuticular wax increases leaf reflectance of infra-red radiation, which decreases the net amount of non-photosynthetically active radiation that is adsorbed by the canopy and the subsequent shedding of latent heat through transpiration (Ebercon et al., 1977; Blum, 1975). Hsiao et al. (1976) defined osmotic adjustment as the process by which plants accumulate solutes within cells to create solute and matric potential gradients that regulate water flow in the xylem and maintain turgor through gradients of hydraulic resistance within the plant. In sorghum, it has been observed that osmotic adjustment in response to water stress improves rooting depths and harvest indexes (*HI*) (Santamaria et al., 1990).

Under deficit irrigation, root growth and development and corresponding soil water uptake vary significantly in space and time. Management practices that promote greater root densities have the potential to reduce evaporation from the soil in favor of transpiration from the crop through increased root water extraction (Gardner, 1964). Shallow rooting depths and low root densities often require frequent, shallow irrigation applications that result in a greater percent of irrigation lost to evaporation. Howell et al. (2007) found that WUE slightly increased for sorghum grown under deficit irrigation on a Pullman clay loam soil. They found that under deficit irrigation, sorghum extracted soil water from 1.7 m compared to extraction from depths less than 1.2 m for sorghum under full irrigation. This capability enables grain sorghum to more efficiently utilize stored soil-water and may permit less frequent but timely irrigation applications for grain production in water-limited environments. Sinclair et al. (1984) reported that short-season cultivars in combination with a deficit irrigation strategy produce a greater WUE and harvest index (*HI*) before the available water supply is depleted. Although short-season cultivars have the potential to increase water savings, as they require fewer days and less water to reach maturity, yield potential is limited compared with cultivars that require a greater number of days to reach maturity. Consequently, mid-season cultivars offer improved yield potential while providing water savings under deficit irrigation.

As early as 1940, both Kramer and Coile and suggested that root extension into moist soil is an important mechanism to sustain plant water uptake. Plants are able to adapt their root architecture and water uptake in response to temporally and spatially variable soil water patterns. Mayaki et al. (1976) demonstrated that with increased water stress, root growth of grain sorghum proceeds at a greater rate than foliage growth. Therefore, the promotion of early season root growth ensures the plant will have an adequate root system to acquire stored soil water at deeper depths during periods of peak evapotranspiration (*ET*). Klepper (1973) showed that longer intervals between irrigation applications enhanced rooting depth of cotton due to the roots' response to temporary soil drying. Deeper rooting systems enable plants to maintain water extraction later in the growing season during critical growth stages (Moroke et al., 2005). However, direct approaches of monitoring root growth (e.g., through soil coring and use of minirhizotrons) are impractical because of the low temporal resolution and high labor-intensive requirements. Indirect methods using measured soil water contents and calculated changes in soil water storage using neutron thermalization (neutron moisture gages) have been used to infer the fractional distribution of roots with depth with some success (Moroke et al., 2005; Vrugt et al., 2001; Gardner, 1964).

During the latter portion of the 20th century, grain sorghum production declined on the Texas High Plains in favor of corn that has a greater yield potential when produced under full irrigation. However, the greater yield potential of corn comes at a cost of greater risk when limited well capacities impose short term water stress. Regional producers are now seeking crops that can be incorporated into sustainable agronomic systems that balance water use efficiency while reducing risks associated with corn production. While sorghum has been viewed as a low input, dryland crop across the region, production patterns are shifting to incorporate sorghum in irrigated systems.

The goal of this research was to evaluate the influence of restricted irrigation on the water use efficiency of grain sorghum and associated root proliferation as inferred by the spatio-temporal dynamics of root water uptake. The objectives of the proposed research were to assess the influence of deficit irrigation strategies on yield and yield components and accompanying WUE of grain sorghum, and examine the effect of deficit irrigation strategies on the profile variability and temporal dynamics of stored soil water.

CHAPTER II

DEFICIT IRRIGATION EFFECTS ON YIELD AND YIELD COMPONENTS OF GRAIN SORGHUM

II.1 INTRODUCTION

Grain sorghum is a drought tolerant crop that is suitable for deficit irrigation due to its physiological adaptability to short-term water stress. Although grain sorghum can withstand prolonged periods of water stress, such tolerance comes at the expense of reduced yield (Assefa et al., 2010; Peacock, 1982). Delineating crop reproductive responses under water-stressed field conditions is critical to the adoption of management strategies that minimize yield losses under deficit irrigation.

Historically, irrigation practices on the Texas High Plains have been related to well water yields during peak demand periods, but due to declining well capacities and water district restrictions, historical irrigation practices are no longer viable. As a result of limited water for irrigation, water not land is becoming the limiting resource in the Texas High Plains production agriculture. Because irrigation helps mitigate production risks in semi-arid zones while improving crop quality and value (Wagner, 2012), research to understand crop responses to the amount and timing of irrigation is essential. With the foresight of limited water resources, Garrity et al. (1982) predicted that irrigated agriculture was entering the “age of management” whereby water deficits could not be avoided, but should be anticipated and managed. As producers adopt conservation measures driven by limited water supplies and social pressures, irrigation management strategies that concentrate water during critical growth stages or employ supplemental irrigation rather than traditional fully irrigated practices could potentially stabilize crop production and an agriculturally driven economy for an extended period (Bordovsky et al., 2011).

A promising management strategy for improving water use efficiencies is deficit irrigation, which attempts to optimize the use of irrigation water and precipitation (English, 1990). Traditionally, deficit irrigation entailed irrigation at a fraction of what the crop would use if water were not limited (Howell, 2007). However, a more intensified management approach considers the dynamics of crop water use throughout the growing season (Vadez, 2013). An optimally managed deficit irrigation strategy may also depend on the amount and depth distribution of water stored in the soil profile at the time of planting. Accordingly, two important components of managed deficit irrigation are (i) the attempt to minimize evaporative losses of water directly from the soil, which occurs during the early part of the cropping season when the fraction of soil covered by the crop is small, and (ii) to concentrate irrigation at stages of crop growth critical to determining potential yield. These two components must be considered together, not independently, as increases in yield may not always be achieved through maximization of water extraction by the plants. While water stress at any stage can reduce sorghum yield, water stress during the reproductive stage of sorghum is the most detrimental (Assefa et al., 2010). With grain sorghum, it has been well documented (Van Oosterom and Hammer, 2008; Tolk et al., 2013; Prasad et al., 2008; Blum, 2005; Crauford and Peacock, 1993; Peacock, 1982; Eck and Musick, 1979) that water stress from growing point differentiation through half-bloom suppresses grain yield due to reduced grain number. Growing point differentiation is the initial stage of reproductive development in grain sorghum (Vanderlip and Reeves, 1979). At growing point differentiation, the crop begins to rapidly develop; 7 to 10 leaves have expanded and rapid nutrient uptake has begun. Between growing point differentiation and half-bloom are the flag and boot stages. At the flag stage, the final leaf (flag leaf) is visible, and the head is developing. At the boot stage, all leaves have expanded and the head is enclosed in the flag sheath. Water stress during the boot stage minimizes head exertion from the flag leaf sheath, which reduces pollination (Gerik et al., 2003). Half-bloom is the final stage of reproductive development where approximately half of the sorghum plants in an area has begun flowering. During this half-bloom, water stress may induce floral abortion and decrease grain yield. In contrast, water stress from anthesis through the dough stage may reduce grain mass (Ockerby et al., 2001; Maman et al., 2004). Understanding the effects of the magnitude of water use during these crop developmental phases on grain production is essential to evaluate and incorporate water conservation measures into irrigation practices. It is also imperative that under conditions of limited water, precipitation is considered in the water management plan. The lack of precipitation can potentially magnify yield responses to irrigation treatments (Allen and Musick, 1993; Howell, 2007).

The objectives of this study were to determine the effect of deficit irrigation strategies and resultant plant available water (*PAW*) on sorghum grain yield and associated yield components; specifically, harvest index (*HI*), panicles per unit land area, number of seeds per panicle, and mass of individual seeds. The effect of deficit irrigation strategies on WUE of grain produced was also assessed.

II.2 APPROACH AND RESEARCH PROCEDURES

Research was conducted at the USDA-Agricultural Research Service, Conservation and Production Research Laboratory, Bushland, Texas, USA (35°11′N, 102°5′W; 1170 m elevation) for three growing seasons from 2010 to 2012. Twelve experimental plots (15- by 109-m) in a randomized complete block design were established on a 180- by 109-m field on Pullman clay loam (Fine, mixed, superactive, thermic Torrertic Paleustoll) with < 1% slope. Soil texture and measured water retention characteristics are included in Appendix B and C, respectively. Soil texture was determined using the hydrometer method described by Gee and Bauder (1986). Soil water retention characteristics of the Pullman soil were determined using a pressure plate extractor (Klute, 1986). A mid-season grain sorghum cultivar (DeKalb DKS44-20) was evaluated under four irrigation treatments: full irrigation (FI), deficit irrigation (DI), managed deficit irrigation (MDI), and non-irrigated (NI). Each treatment was replicated three times. Scheduling of FI was based on weekly measurements of precipitation plus change in stored soil water within the rooting zone (0 to 1.6m). Soil water contents were determined using a neutron moisture gage (model 503DR, InstroTek, Inc., Raleigh, NC) from 0.1- to 2.3-m depth in 0.2-m increments at weekly intervals throughout the growing season at two locations in each of the 12 experimental plots. An additional four access tubes were located in MDI plots for a seperate detailed sub-study of MDI with time-domain reflectometry. The neutron moisture gage was previously field calibrated for the Pullman soil for the A, Bt and Btk horizons (Evett and Steiner, 1995) with 1.0% accuracy (Appendix A). The depth of irrigation water applied was 25 to 32 mm to the FI treatment when stored soil water fell below a set managed allowable depletion (MAD) defined as 50% of potential plant available water (*PPAW*) in the rooting zone. *PPAW* was determined as the difference between depth averaged water contents at -33 kPa (0.328 $m^3\ m^{-3}$) and -1.5 MPa (0.197 $m^3\ m^{-3}$) measured in 0.2-m increments throughout the root zone (0 to 1.6 m). Calculated *PPAW* was 210 mm [(0.328 $m^3\ m^{-3}$ – 0.197$m^3\ m^{-3}$) × 1600 mm] for this soil. Deficit irrigation was scheduled at 50% of FI and applied at application depths similar to the FI treatment but less frequently. Managed deficit scheduling was based on a fraction of the cumulative amount of FI and varied with growth stage. During the vegetative growth stage, one or two irrigations were omitted from MDI compared with DI, such that applications amounts for MDI were less than 50% of the FI treatment for that stage. From growing point differentiation to half-bloom (approximately 35 to 70 days after planting for the specified sorghum variety at this site), irrigations for MDI were scheduled at 75% of FI. From half-bloom to physiological maturity, irrigations for MDI were scheduled at 50% of FI. As with DI, MDI irrigation depths were also applied at similar application depths of the FI treatment but less frequently.

Irrigation was applied with a three-span, lateral-move sprinkler system (Model 6000, Valmont Irrigation, Valley, NE). Drop hoses spaced 1.5-m apart were equipped with No. 15 low drift nozzles (0.32 $L\ s^{-1}$) (Senninger Irrigation, Inc., Clermont, FL) at 0.5-m above ground surface, convex-medium grooved spray pads, and 68.9 kPa pressure regulators.

Prior to initiation of experimental plots in 2010, the research field was deep-tilled using a para-plow in the fall of 2009 to partially disrupt a plow pan that formed under previous management. Research plots were deep chiseled each fall, following harvest, using a chisel-chopper drag plow (BJM Sales and Service, Hereford, TX). Plots were tilled twice each spring for weed control and seedbed preparation at a depth of approximately 0.13 m using a three blade 4.5-m sweep plow with one 1.5-m wide center blade and two exterior 1.8-m wide blades.

Experimental plots were sampled and analyzed for fertility requirements in April of each experimental year for a grain-yield goal of 11 Mg ha^{-1} under irrigation and 4 Mg ha^{-1} under non-irrigated treatments. For all experimental years, mean nitrogen and phosphorus recommendations were 180 to 193 kg ha^{-1} N and 29 to 42 kg ha^{-1} P_2O_5, respectively for irrigated treatments. Each May, ammonium polyphosphate (10-34-0) and urea-ammonium-nitrate (32-0-0) were mixed and knifed-in (62 kg ha^{-1} N and 29 kg ha^{-1} P_2O_5) across all irrigated plots as a pre-plant fertilizer to meet the irrigated crop total phosphorus and partial nitrogen requirements. Remaining nitrogen requirements were satisfied through injection and application of 32-0-0 with irrigation water at the 10-leaf stage through the sprinkler system. Fertilizer requirements of the NI crop (40 kg ha^{-1} N and 23 kg ha^{-1} P_2O_5) were knifed-in as a pre-plant fertilizer. The sorghum was planted on 0.76-m row spacing using a Max-Emerge vacuum planter (John Deere, East Moline, IL) at a seeding density of 161,000 ha^{-1} in 2010 and 2011 and 173,100 ha^{-1} in 2012. Bicep II Magnum (Atrazine plus S-metolachlor; Syngenta Crop Protection, LLC) was sprayed as a pre-emergent to control in-season weeds.

Micrometerological variables were monitored using a datalogger (model CR23X, Campbell Scientific, Inc., Logan, UT) and environmental instrumentation located centrally within the experimental field. Measurements were recorded at 0.25-h intervals and included ambient air temperature and relative humidity (model HMP45C Temperature and Humidity Probe, Vaisala Inc., Helsinki, Finland), wind velocity (model 014A wind sensor, MET-ONE Instruments, Inc, Grants Pass, OR), and total global irradiance (model LI-200SA pyranometer, Li-Cor Biosciences, Lincoln, NE) all at 2 m above the surface. Precipitation was measured using a tipping bucket rain gage (TE525M, Texas Electronics, Dallas, TX) and incoming and reflected short and longwave radiation in 2010 and 2012 (models CM14 albedometer and CGR3 pyrgeometer, Kipp and Zonen, Delft, Netherlands), and net radiation (model Q*7.1 Net

Radiometer, REBS, Bellevue, WA) were measured at 0.5 to 1.0 m above the canopy. Reference evapotranspiration (ET_0) was calculated from monitored variables using the ASCE standardized reference evapotranspiration equation at hourly intervals (Allen et al., 2005).

Using weekly neutron gage measurements, crop evapotranspiration (*ET*) was estimated using a water balance approach (Hulugalle and Lal, 1986; Evett et al., 1993):

$$ET = P + I - \Delta S - R - D \tag{1}$$

where *P* is precipitation, *I* is irrigation, ΔS is the change in stored water from 0 to 1.6 m, *R* is net runoff, and *D* is drainage below the root zone. In this study, R and D were assumed negligible (Evett et al., 2012; also see Chapter III for drainage calculations). Using the FAO-56 single time averaged crop coefficient (K_c) approach with time-averaged crop coefficients, FAO-56 predicted evapotranspiration ET_c was calculated as $ET_c = K_c \cdot ET_0$ (Allen et. al, 1998). ET_0, ET_c, and *ET* were evaluated from crop emergence through physiological maturity.

Grain and aboveground biomass were sampled at physiological maturity from three 9-m^2 subsamples in each plot. Panicles were separated from the stover, dried at 60°C for one week and hand threshed using a mechanical belt thresher (Agriculex Inc., Guelph, Ont. Canada) to determine grain yield and yield components (areal density of plants, tillers and panicles, mass $seed^{-1}$, seed grain per panicle, and *HI*). Grain yield was corrected to 0.13 kg kg^{-1} wet mass basis. Stover samples were dried at 60°C for one week and weighed to determine yield of above-ground biomass when combined with the weight of panicles. Above ground biomass was reported on an oven dry equivalent. Average seed mass was determined from two, 200-seed count samples. The number of seed grains per panicle was calculated from total grain dry mass per panicle divided by the average seed mass as described by Lafarge et al. (2002). *HI* was calculated as the ratio of grain yield to total aboveground biomass using oven dry equivalent weights. WUE (kg m^{-3}) was calculated as the ratio of grain yield (corrected to 0.13 kg kg^{-1} moisture) to *ET* (m).

The duration of growth periods can be related to maximum and minimum temperatures (Prasad et al., 2008; Lobell and Ortiz-Monasterio, 2007), through the concept of growing degree day (Celcius, GDD_c) accumulation (Eq. 2). Growing degree days (°C) for crop development were calculated as:

$$GDD_c = \Sigma([T_{max} + T_{min}]/2) - T_b \qquad (2)$$

using a baseline temperature (T_b) of 10°C (Peacock and Heinrich, 1984). Maximum daily temperature (T_{max}) was the lesser of the daily maximum temperature or 37.8°C, and minimum daily temperature (T_{min}) was either the daily minimum temperature or 10°C, whichever was greater.

Statistical analysis was completed using the general linear procedure (SAS Institute, 2004) to test for significant irrigation treatment effects on dependent variables yield, yield components, seasonal water use and water use efficiency. The NI (dryland) treatment was omitted in all statistical tests because of crop failure in two out of the three seasons. In most cases, irrigation effects were examined separately within each year because of significant year by irrigation interactions. Confidence intervals and adjusted least significant differences for multiple comparisons were determined using Tukey's HSD. Correlations were evaluated based on the Pearson correlation coefficient. Effects and comparisons were declared significant at $\alpha = 0.05$ probability level.

II.3 RESULTS AND DISCUSSION

II.3.1 Growing Season Conditions

Environmental conditions varied considerably among the three study years with near normal conditions in 2010, above average temperatures and abnormally low seasonal precipitation in both 2011 and 2012 (Table 2-1). In 2010, annual precipitation was 483 mm; slightly above the 73-year (1939-2012) mean precipitation of 463 mm at Bushland, TX. Annual precipitation was substantially lower than the 73-year mean in 2011 and 2012 which totaled 170 and 213 mm, respectively (Fig. 2-1). Precipitation occurring during the growing season of all experimental years was below the 73-year seasonal mean of 249 mm (Fig. 2-1). Of the long-term mean seasonal precipitation received at

Bushland, TX, 26% (64 mm) is received during July. In a review of previous research on the High Plains, Staggenborg et al. (2008) reported that July precipitation is most beneficial for sorghum grain yields, which coincides with the reproductive period of sorghum in this region. The authors specified that in a rain-fed cropping system, grain sorghum yields increased 0.1 to 0.2 Mg ha^{-1} for each cm precipitation received in July. Regardless of precipitation timing, water availability at critical growth stages is often of greater importance than annual precipitation (Larfarge et al., 2002). Of the 180.5 mm of precipitation received during the growing season in 2010, 51% occurred in the month of July coinciding with the critical growth period. Nevertheless, precipitation received after July of 2010 was nominal resulting in below average seasonal precipitation. Growing season precipitation in 2011 and 2012 totaled 61.2 and 34.5 mm, respectively. In addition to minimal growing season precipitation in 2010 and 2011, winter and spring precipitation was inadequate to refill soil profiles.

From May 15 through September 15, maximum daily temperatures exceeded the 73-year mean maximum daily temperature (31.6ºC) of this period on 79 days in 2010, 102 days in 2011 and 95 days in 2012 (Fig. 2-2). In 2011, there were 46 days during the growing season that had daily maximum temperatures exceeding 38ºC; 22 of those days occurred between growing point differentiation and half-bloom. Seasonal daily maximum air temperatures were milder in 2010, although from emergence through vegetative development there were 13 days with temperatures that exceeded 35°C. After growing point differentiation in 2010, maximum daily temperatures approached the 73-year mean maximum temperature (<35ºC, Fig. 2-2). Maiti et al. (1996) defined optimum growing temperatures for sorghum as 21 to 35°C for germination, 26 to 34° for vegetative growth and development, and 25 to 28°C for reproductive growth. As a result of elevated temperatures in 2011, the duration between growth stages was longer than in 2010 and 2012 due to the effect of the temperature on growth and development (Table 2-2). While seasonal temperatures in 2012 were also greater than the long-term mean, the mean daily maximum temperature between growing point differentiation and half-bloom was 36°C and, as a result, the duration between these stages was eleven days shorter than 2011 (Table 2-2).

Table 2-1. Daily mean, maximum and minimum climatic variables from planting through maturity at Bushland, Texas.

	24 hour Climatic Means		
	2010	2011	2012
Tmean (°C)	24.9	26.6	25.4
Tmax (°C)	38.6	43.8	42.2
Tmin (°C)	21.0	14.4	17.0
Vapor Pressure Deficit (kPa) Mean	1.43	2.84	1.81
Vapor Pressure Deficit (kPa) Max	2.68	4.60	3.30
Vapor Pressure Deficit (kPa) Min	0.39	0.31	0.17
Mean 2-m Wind Speed (m s^{-1})	4.26	4.03	4.28
Max 2-m Wind Speed (m s^{-1})	6.55	7.70	7.59
Min 2-m Wind Speed (m s^{-1})	2.10	1.32	1.78
Solar Radiation (MJ m^{-2} d^{-1}) Mean	25.6	28.6	25.0
Solar Radiation (MJ m^{-2} d^{-1}) Max	32.8	36.8	32.6
Solar Radiation (MJ m^{-2} d^{-1}) Min	7.40	4.92	6.06
Net Radiation (MJ m^{-2} d^{-1}) Mean	12.8	13.0	11.8
Net Radiation (MJ m^{-2} d^{-1}) Max	18.1	20.3	18.1
Net Radiation (MJ m^{-2} d^{-1}) Min	2.95	2.26	2.63

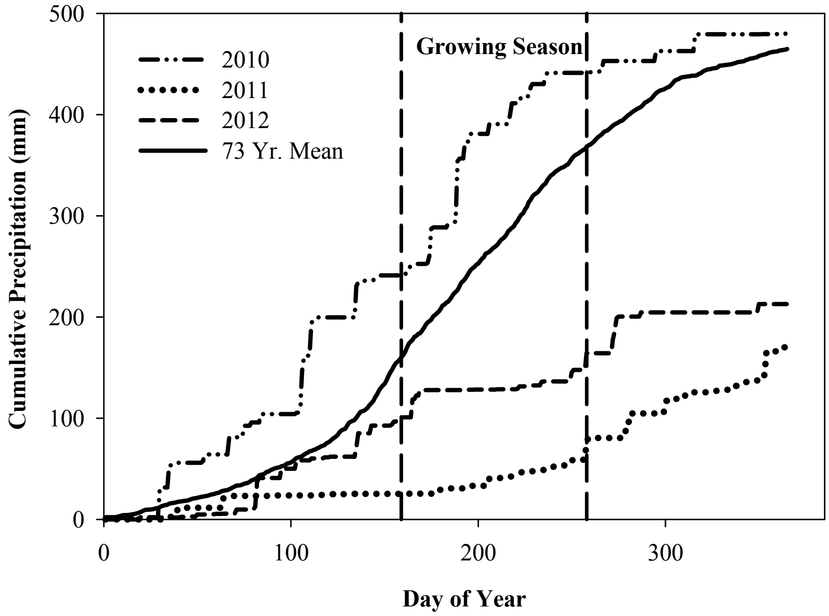

Figure 2-1. Annual and growing season precipitation during study period compared with 73 year (1939-2012) mean precipitation at Bushland, Texas.

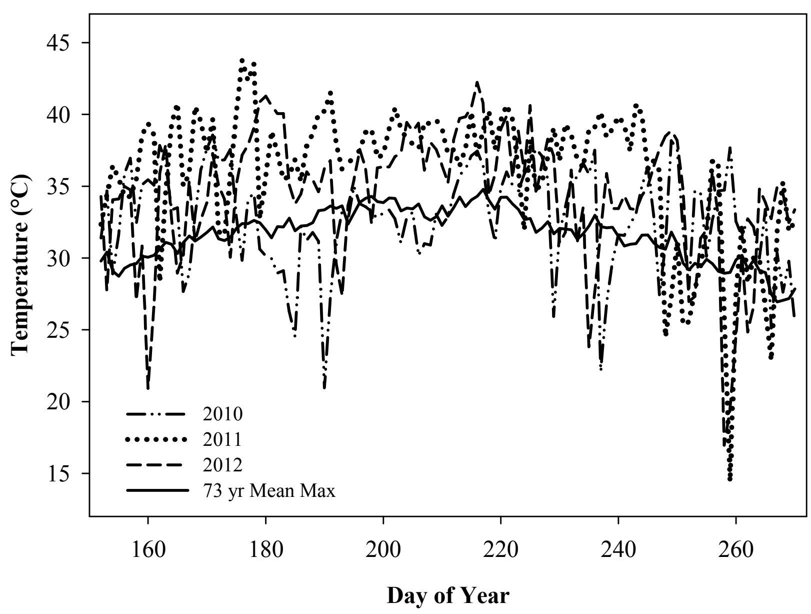

Figure 2-2. Maximum daily temperatures at Bushland, TX for all years of the study compared with the 73 year (1939-2012) mean maximum temperature.

In 2010 and 2012, greater accumulation of GDD_c was achieved during the vegetative stage compared with 2011 because the duration between planting and five-leaf stage was an average of six days longer than the same period in 2011 (Table 2-2). Elevated temperatures during the vegetative stage in 2011 resulted in a more rapid progression of the vegetative period and thus fewer *GDDc*. However, crop development under both DI and MDI treatments in 2011 was delayed due to elevated temperatures between growing point differentiation through half-bloom compared with sorghum under FI which reached half-bloom stage nine days earlier. As a result, fewer GDD_c were accumulated under FI than either deficit irrigated treatments. Machado and Paulsen (2001) reported that elevated temperatures do not significantly affect yield when the crop has sufficient water, but the combination of high temperatures and limited water negatively influence crop development (Crauford and Peacock, 1993; Donatelli et al., 1992; Blum, 2005; Prasad et al., 2008). Developmental delay in sorghum often occurs under water stress resulting in increased cumulative GDD_c (Donatelli et al., 1992) as was observed in 2011 under DI and MDI (Table 2-2). The earlier planting date in 2012 resulted in the half-bloom to soft dough period occurring two weeks earlier than in 2011. Consequently, the crop had to tolerate a longer period of elevated temperatures during grain fill in 2012. While optimum planting dates appear to be regional and year specific, a planting date targeted to avoid heat stress during anthesis has usually been a successful strategy (Vanderlip, 1979).

Table 2-2. Observed developmental stages and respective cumulative growing degree reported in Celcius (GDD_c) for al years. There were no differences between developmental progression at specific growth stages at observed days of year (DOY) in 2010 and 2012. In 2011, full irrigation (FI) and deficit irrigation treatments (deficit irrigation and managed deficit irrigation (DI and MDI, respectively)) are reported seperately. (GPD = growing point differentiation)

	2010		**2011 - FI**		**2011 - DI&MDI**		**2012**	
Growth Stage	**DOY**	**GDD_c**	**DOY**	**GDD_c**	**DOY**	**GDD_c**	**DOY**	**GDD_c**
Planting	162	0	161	0	161	0	152	0
Emergence	169	109	168	109	168	109	161	86
5 Leaf	187	378	178	278	178	278	179	386
GPD	197	525	188	446	188	446	191	598
Boot	214	790	213	909	220	1039	205	831
Half -loom	221	847	220	1039	229	1196	214	997
Soft Dough	239	969	237	1347	244	1479	226	1220
Hard Dough	253	1134	246	1513	255	1609	236	1367
Black Layer	260	1235	256	1624	264	1708	251	1589
Total Days to Maturity	98		95		103		99	

II.3.2 ET_0 and Water Use

Cumulative ET_0 during the growing season was greatest in 2011 (854 mm; Table 2-3; Fig. 2-3) whereas it did not greatly differ between 2010 and 2012, which totaled 624 and 638 mm, respectively. Plant available water was evaluated within the root zone to 1.6 m because mean change in water content from 1.6 to 2.2 m was not significantly different from zero ($p \geq 0.210$) for all irrigation strategies and because drainage below 2.2 m was negligible (see Chapter II).

Effect of irrigation treatment on soil water storage depended on the cropping year (p=0.001). In 2010, reduced irrigation under both deficit irrigation treatments resulted in additional soil water extracted to 1.6 m compared with FI as surmised by the change in soil water storage from emergence to maturity (Table 2-3; 46 mm (± 16 s.d.) under DI and 45 mm (± 12 s.d.) under MDI). Reduced seasonal irrigation under DI also coincided with additional soil water extraction under DI in 2011 (38 mm ± 18 s.d.) compared with FI. In 2012 however, seasonal change in storage was comparatively large (107 to 119 mm) with no significant differences among irrigation treatments (<15 mm). Among all years and irrigation treatments, change in storage contributed ≤38.0 % of the water requirement to *ET*. As such, maintaining 50% managed allowable depletion within the soil profile resulted in precipitation and irrigation being the primary components of *ET*.

Table 2-3. Changes in soil water storage and total seasonal water use including irrigation and precipitation for all seasons and full irrigation (FI), managed deficit irrigation (MDI), and deficit irrigation (DI) treatments.

Plot	Year	ΔS	Precip.	Irrig.	*ET* †
		----------------------	mm	----------------------	
DI	2010	-92.0	180.5	132.8	405.3±13.2
FI	2010	-46.1	180.5	322.3	548.9±3.9
MDI	2010	-91.4	180.5	164.6	436.5±0.7
DI	2011	-28.2	61.2	332.0	421.4±6.7
FI	2011	9.5	61.2	608.6	660.3±11.5
MDI	2011	-4.3	61.2	388.6	454.1±2.8
DI	2012	-119.0	34.5	152.4	305.9±8.4
FI	2012	-107.2	34.5	304.8	446.5±3.2
MDI	2012	-117.8	34.5	177.8	330.1±0.5

†*ET* standard deviation based on variations in change in plot soil water storage from emergence to maturity.

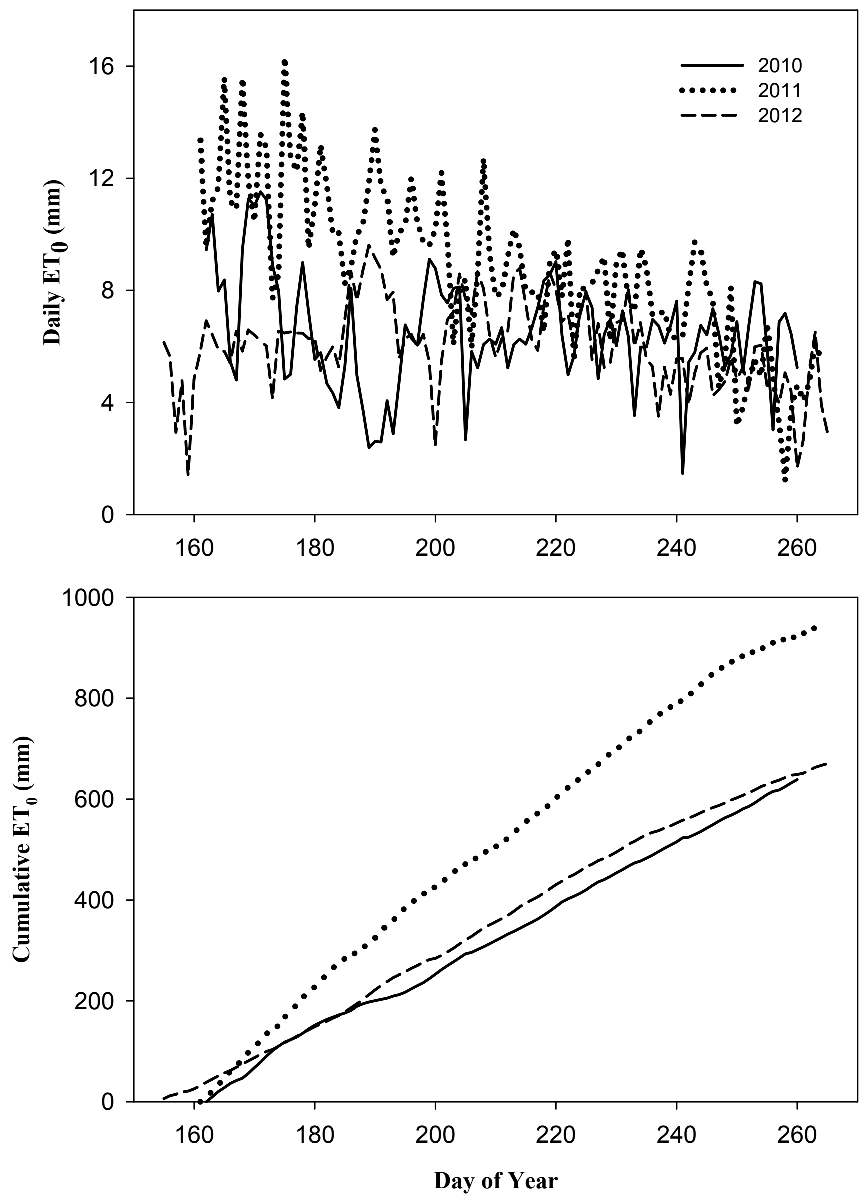

Figure 2-3. Daily ET_0 computed from within field standard meteorological measurements for all experimental years.

Plant available water to 1.6 m depth (*PAW*) at emergence was significantly different among years (p = 0.009) with 2011 exhibiting the lowest initial soil water contents (Table 2-4). While there were no differences in *PAW* among treatments in 2010 and 2011 (p = 0.558), in 2012 the FI plots had marginally greater (33 mm; p = 0.051) soil water contents compared with DI and MDI (Table 2-4). Seasonal irrigation depths were greatest in 2011 for all irrigation strategies compared with 2010 and 2012 as a combined result of low *PAW* at emergence and high cumulative ET_0 (885.7 mm) during the growing season (Table 2-4). Seasonal irrigation depths were similar in 2010 and 2012.

Table 2-4. Plant available water at emergence, half-bloom and hard dough with associated standard deviations for all years and full irrigation (FI), managed deficit irrigation (MDI), and deficit irrigation (DI) treatments.

		Plant Available Water					
Plot	**Year**	**Emergence**	**Stdev**	**Half-Bloom**	**Stdev**	**Hard Dough**	**Stdev**
		-----------------------------------mm-----------------------------------					
DI	2010	158	26	96	19	91	16
FI	2010	146	8	141	13	118	12
MDI	2010	155	20	114	19	99	19
DI	2011	91	31	72	19	63	28
FI	2011	96	19	89	17	110	36
MDI	2011	91	25	91	19	82	31
DI	2012	148	33	51	20	36	17
FI	2012	191	18	99	22	100	16
MDI	2012	168	31	62	26	55	26

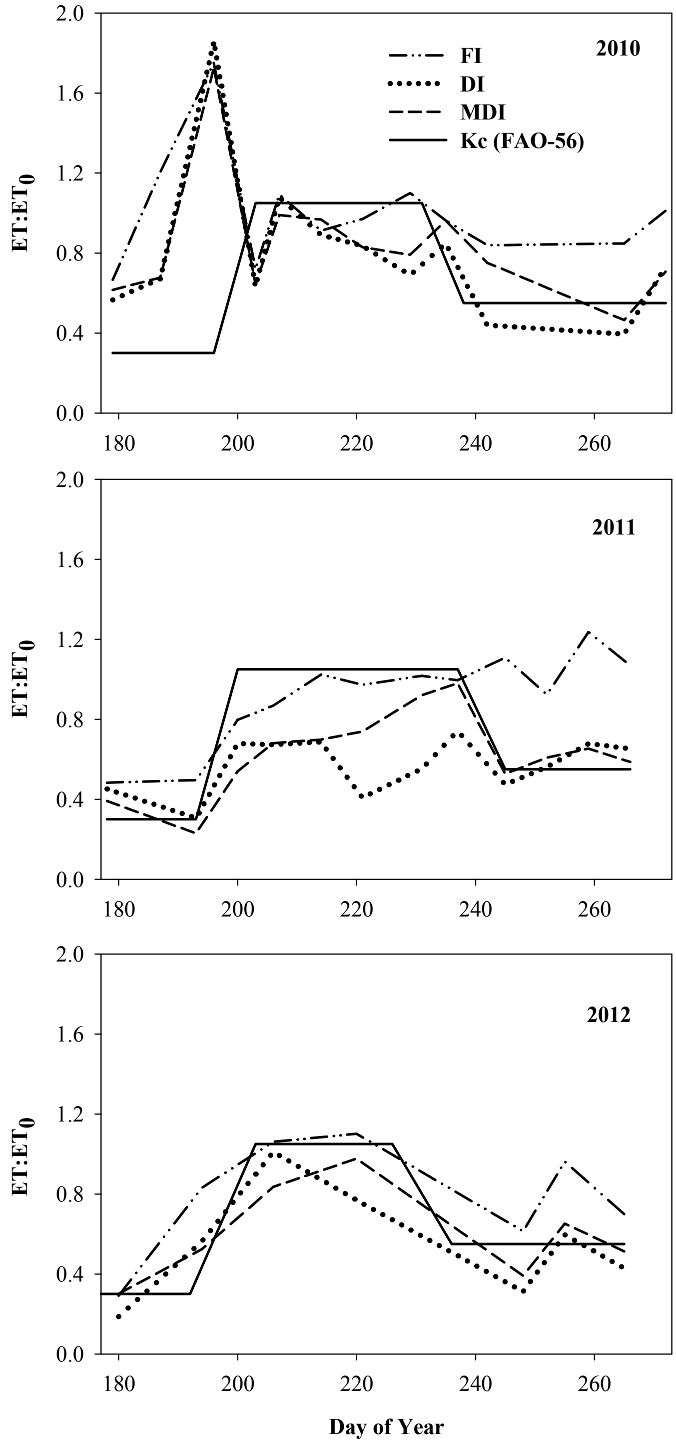

Figure 2-4. Ratio of water use (*ET*) to potential evapotranspiration (ET_0) and the corresponding FAO-56 crop coefficient (K_c) for grain sorghum for the three cropping years and full irrigation (FI), managed deficit irrigation (MDI), and deficit irrigation (DI) treatments.

Inspection of the actual (ET:ET_0) and FAO-56 predicted ($K_c = ET_c$:ET_0) ratios of crop water use to ET_0 for FI prior to growing point differentiation (Fig. 2-4) demonstrates that predicted water use (K_c :ET_0 with $K_c = 0.3$; Allen et al., 1998) underestimated actual water use (ET) in all years of the study. Differences in ET and ET_c prior to canopy closure likely arise from an underestimation of evaporation by FAO-56, especially following irrigation and precipitation events. Nonetheless, for all treatments in 2010 and 2012 and FI in 2011, *PAW* increased during the vegetative stage due to irrigation and precipitation in excess of ET (Fig. 2-4). DI sorghum exhibited a lower ET from growing point differentiation through maturity for all years compared with MDI at the expense of greater irrigation during the earlier vegetative stage. This is characterized in Fig. 2-4 as the intersection of the water use curves of MDI and DI at approximately boot stage. In 2012, *PAW* for all irrigation strategies declined at a steady rate and never recovered to pre-emergence levels.

II.3.3 Grain Yield Response to Irrigation Treatments

Mean grain yields of FI plots exceeded yields of MDI and DI in all three years ($p < 0.001$) (Fig. 2-5; Table 2-5). The influence of deficit irrigation strategy on yield was year dependent ($p < 0.001$). Mean grain yields of MDI were greater than yields of DI in all years, although only significantly greater in 2010 and 2012 ($p = 0.009$ and $p < 0.001$, respectively). While yields of MDI were 1.0 to 1.3 Mg ha^{-1} greater than DI in 2010 and 2011, respectively, the MDI yield (4.1 Mg ha^{-1}) was 237% greater than that of DI (1.7 Mg ha^{-1}) in 2012 (Fig. 2-5). There were no significant differences between yields of the same irrigation treatment in 2010 and 2011 ($p \geq 0.283$). In 2012, yields of all irrigation treatments were significantly lower than yields of previous years. The 2012 FI yield was comparable to the 2010 and 2011 deficit treatment irrigated yields.

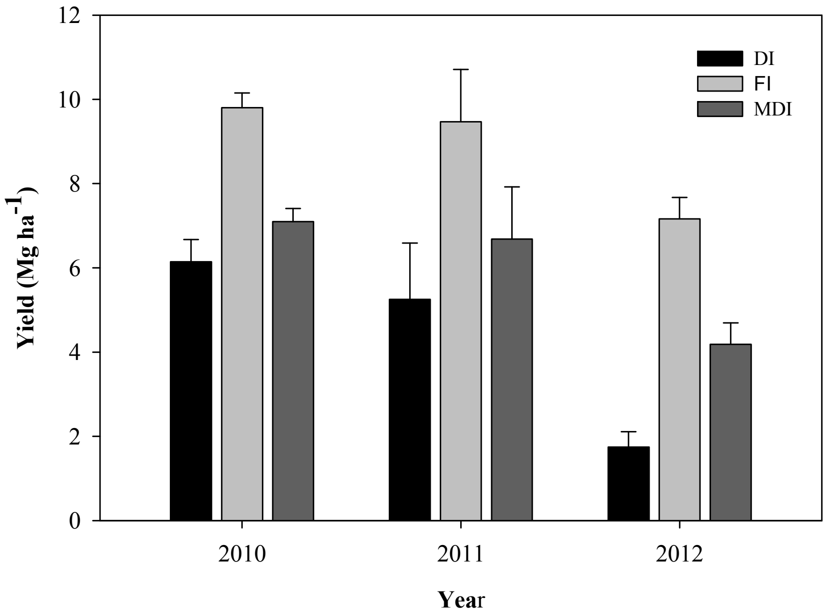

Figure 2-5. Seasonal grain yield (13% Moisture) with bars indicating plus 95% confidence for full irrigation (FI), managed deficit irrigation (MDI), and deficit irrigation (DI) treatments.

Yield reductions associated with water deficits at different growth stages can be related to the deviations in the magnitude of yield components; specifically, plant density, tiller production, areal density of panicles, panicle mass, number of seeds per panicle (SPP), and average seed mass (Tables 2-5 and 2-6). Variability in plant density among years (10.0 to 14.0 m^{-2}) was likely due to reduced *PAW* at emergence in 2011 and greater seeding rates in 2012; however, there were no consistent trends among irrigation treatments. While plant density was lower under DI in 2010 and 2011 compared with other treatments ($p < 0.001$), irrigation treatment effect did not significantly influence plant density in 2012 ($p = 0.895$). In 2011, there was significantly greater plant density under FI compared with MDI ($p = 0.043$); although, there were no differences between MDI and DI ($p = 0.473$) and FI and DI ($p = 0.362$). While increased plant density can potentially increase yield potential, there were no consistent relationships between plant density and the aerial density of panicles. The areal density of panicles ranged from 13.0 to 19.0 m^{-2} during the three study years. Each year, the greatest panicle density was achieved under FI ($p < 0.001$) with the greatest panicle density for all treatments occurring in 2011 (Table 2-6).

Table 2-5. Yield (13 % moisture), abovegroung biomass (oven-dry basis) and harvest index for all years and full irrigation (FI), managed deficit irrigation (MDI), and deficit irrigation (DI) treatments.

Year	Irrigation Strategy	Yield ($Mg\ ha^{-1}$) 13% Moisture	Aboveground Biomass ($Mg\ ha^{-1}$) OD basis	Harvest Index
2010	FI	$9.8^{a\dagger}$	18.8^{a}	0.46^{a}
2010	MDI	7.1^{b}	13.0^{b}	0.47^{a}
2010	DI	6.1^{c}	12.2^{b}	0.44^{a}
2010	NI	$3.1^{\ddagger}$	9.5	0.30
2011	FI	9.5^{a}	18.3^{a}	0.45^{a}
2011	MDI	6.6^{b}	12.7^{b}	0.44^{a}
2011	DI	5.3^{b}	12.3^{b}	0.39^{a}
2011	NI	0	0.20	0
2012	FI	7.2^{a}	13.7^{a}	0.46^{a}
2012	MDI	4.1^{b}	8.9^{b}	0.41^{a}
2012	DI	1.7^{c}	5.8^{c}	0.26^{b}
2012	NI	0	0.23	0

†different letters in columns within the same year indicate signficant differences at the 0.05 level using Tukey's adjusted means comparison test.
ǂ NI plots not statistically evaluated due to crop failure in 2011 and 2012.

In sorghum, tillering enables plants to increase panicle production and thereby regulate yield under varying levels of available water, environmental stress, or plant population densities. Areal density of tillers ranged from 2.9 to 7.2 m^{-2} during the three study years (Table 2-6). While the greatest numbers of tillers were observed in 2011 (6.0 to 7.2 m^{-2}), there were not any significant differences between fertile tillers in 2010 and 2011 for FI and MDI treatments ($p = 0.339$). In all years, DI produced the fewest fertile tillers. However, in comparison to all seasons, the areal density of tillers was significantly lowest in 2012 for all treatments ($p < 0.001$). In 2012, there were not any fertile tillers produced under MDI and DI, and those produced under FI were the lowest compared with the other years for this irrigation treatment (0.409 m^{-2}). While results suggest suppressed tillering under greater plant populations in agreement with the results of Jones and Johnson (1991), it is likely that fewer tillers were produced under elevated water stress in 2012 because, the available water was used by the crop to maintain the primary plant.

Seeds per panicle (SPP) were significantly greater ($p < 0.001$) under FI for all years although the effect of deficit irrigation strategies (DI and MDI) on SPP was year dependent. Mirroring grain yield, SPP under all irrigation treatments were greatest in 2010 compared with 2011 and 2012 ($p < 0.001$). Additional precipitation and near normal temperatures in 2010 during the critical growth period likely facilitated improved growing conditions which resulted in greater SPP compared with 2011 and 2012 for all irrigation treatments. While exposure to extreme high temperatures for periods longer than ten days between vegetative development and growing point differentiation can result in decreased seed set (Prasad, 2008; Chowdhury and Wardlaw, 1978), water stress between half-bloom and soft dough can inhibit pollen development, pollination of the ovule, and prompt abortion of fertilized ovules (Assefa et al., 2010; Gerick et al., 2003; McWilliams, 2003). Elevated temperatures at growing point differentiation of 2011 and 2012 are likely responsible for the lower SPP in these years as seen in the reduction in SPP under FI compared with 2010 (Fig. 2-6, Table 2-6). Water stress between half-bloom and soft dough reduced SPP under MDI and DI compared with FI. Most notably, in 2012, SPP under MDI and DI was 30 and 74%, respectively, of SPP under FI (Fig. 2-6, Table 2-6). In 2011 and 2012, grain yield was correlated to SPP ($r^2 \geq 0.874$, $p \leq 0.002$), and yield increased with increasing SPP (Fig. 2-6). However, in 2010, the SPP and yield relationships were inconsistent (Fig. 2-6) with weak correlations for FI and MDI ($r^2 \leq 0.423$, $p \geq 0.257$). Under MDI and FI, it is likely that the crop was approaching maximum yield potential for the respective irrigation level.

Table 2-6. Evaluated yield components for all years and full irrigation (FI), managed deficit irrigation (MDI), and deficit irrigation (DI) treatments.

Year	Irrigation Strategy	Aerial Density m^{-2} Plants	Tillers	Panicles	Seed $Panicle^{-1}$	Seed Mass (mg $seed^{-1}$)
2010	FI	11.0[a†]	4.3[a]	14.9[a]	2317.2[a]	25.4[a]
2010	MDI	10.9[a]	4.7[a]	14.6[a]	1765.1[b]	24.2[ab]
2010	DI	10.0[a]	5.2[a]	13.0[b]	1841.1[b]	22.6[b]
2011	FI	13.3[a]	7.2[a]	18.9[a]	1637.5[a]	27.2[a]
2011	MDI	11.4[b]	6.0[a]	16.8[ab]	1443.0[a]	24.0[b]
2011	DI	12.3[ab]	6.8[a]	15.4[b]	1079.9[b]	27.7[a]
2012	FI	13.8[a]	4.5[a]	15.7[a]	1455.5[a]	27.9[a]
2012	MDI	14.0[a]	3.1[b]	13.9[b]	1037.4[b]	25.3[b]
2012	DI	13.9[a]	2.9[b]	13.0[b]	533.0[c]	22.6[c]

†different letters in columns within the same year indicate signficant differences at the 0.05 level using Tukey's adjusted means comparison test.

Seed mass was significantly different between irrigation treatments; however, there were no consistent trends among seed mass and irrigation treatments (Table 2-6). Additionally, seed mass and yield for all irrigation treatments and years were not found to be correlated ($r^2 \leq 0.641$, $p \geq 0.063$, Fig. 2-7). Inconsistent differences in seed mass in conjunction with negligible correlations in seed mass and yield relationships suggest that water use between growing point differentiation and half-bloom had more impact on total SPP and thus grain yield compared with water use during the vegetative or ripening stages as also identified by numerous sources (Assefa et al., 2010; Maman et al., 2004; Ockerby et al., 2001; Craufurd et al., 1993). Seed mass of DI sorghum was significantly lower ($p < 0.001$) than seed mass of FI sorghum in 2010 and 2012. Reduction in seed mass under DI is reflective of decreased soil moisture available for seed fill during soft dough compared with MDI and FI. While it has been observed that SPP is the governing component in sorghum grain yield (Tolk et al., 2013; Van Oosterom and Hammer, 2008; Crauford and Peacock, 1993), seed mass has the potential to stabilize yield by

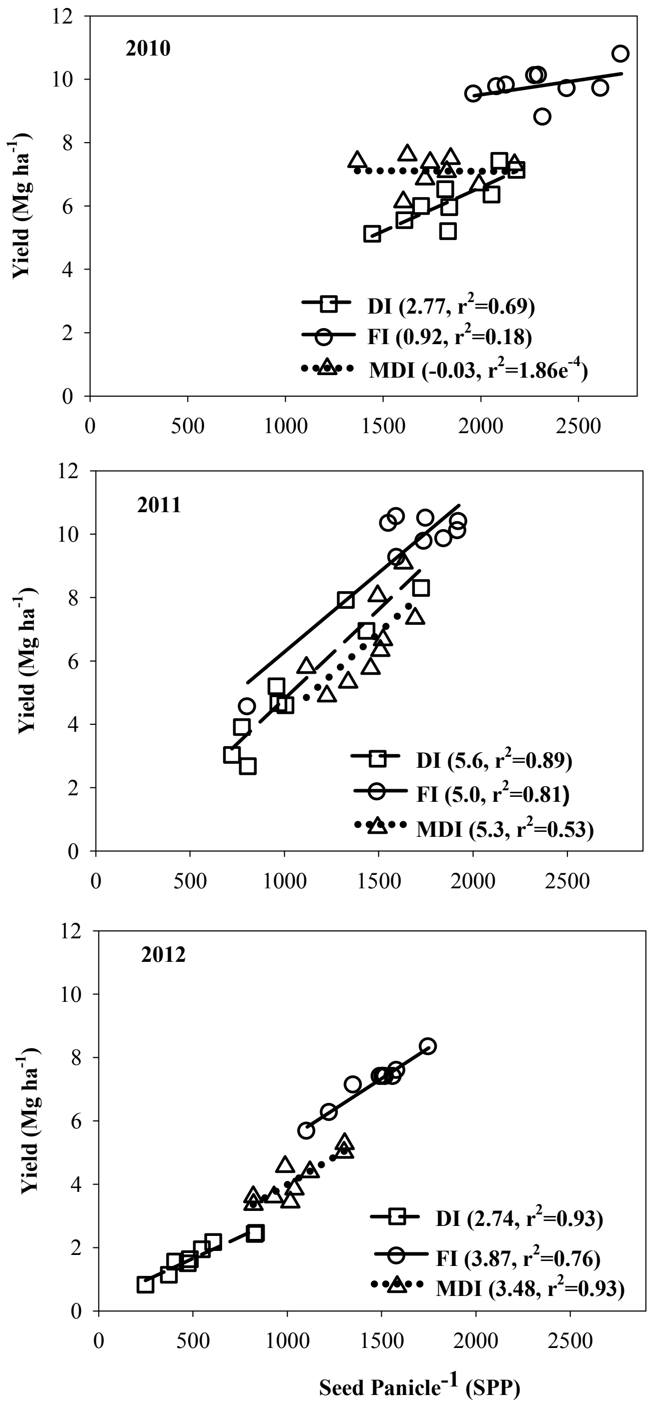

Figure 2-6. Relationship between yield (kg ha^{-1}) and the number of seeds panicle^{-1}for all years and full irrigation (FI), managed deficit irrigation (MDI), and deficit irrigation (DI) treatments. The slope of the regression and the correlation coefficient for the respective irrigation treatment is in parentheses.

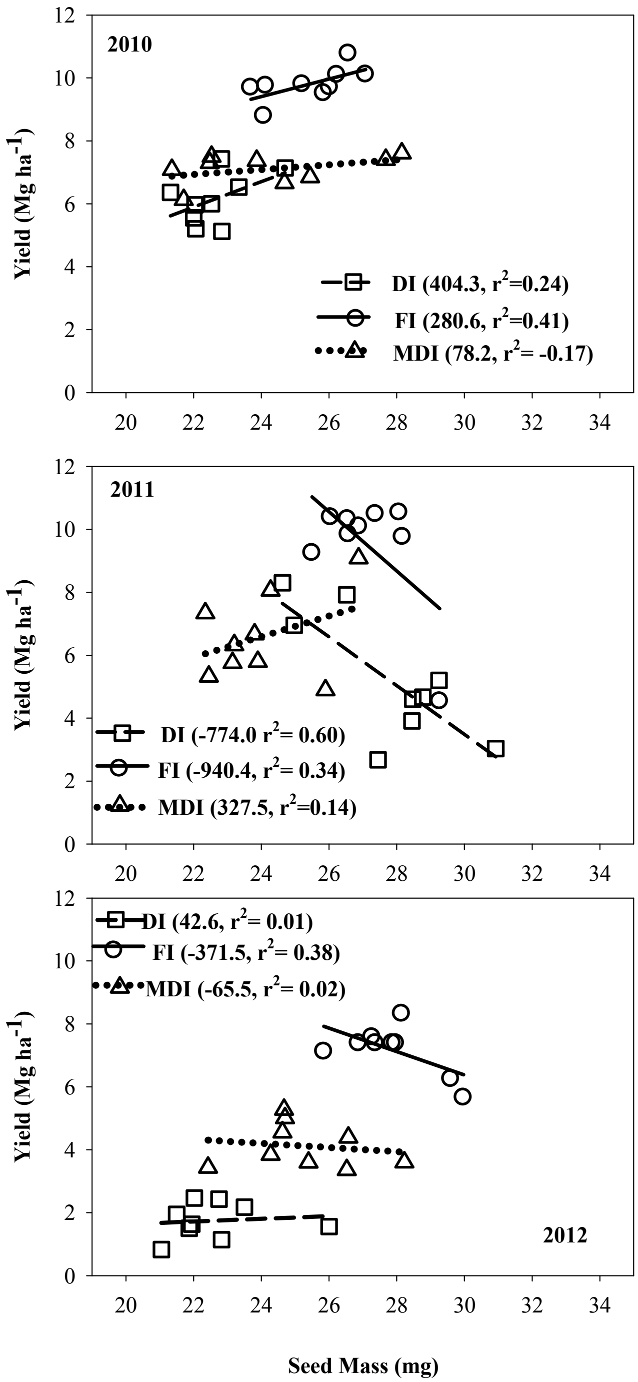

Figure 2-7. Relationship between yield and seed mass for all years and full irrigation (FI), managed deficit irrigation (MDI), and deficit irrigation (DI) treatments. The slope of the regression and the correlation coefficient for the respective irrigation treatment is in parentheses.

compensating for reductions in SPP (Tolk et al., 2013). However, in this study, we did not have conclusive evidence of this trend (Fig. 2-7).

Total aboveground biomass ranged from 5.8 to 18.8 Mg ha-1 (oven dry basis) during the three study years (Table 2-5). Greatest aboveground biomass production occurred under FI, which was significantly greater compared with DI and MDI in all years ($p < 0.001$). Aboveground biomass under DI and MDI were not significantly different in 2010 and 2011 ($p = 0.947$). Measured aboveground biomass in 2012 was significantly lower under all treatments from the two prior years in addition to significant differences between all irrigation treatments ($p < 0.001$).

There were no significant differences in *HI* among irrigation strategies in 2010 and 2011 ($p \geq 0.297$). However, *HI* was significantly lower (0.26) under DI compared with MDI (*HI* = 0.41) and FI (*HI* = 0.46) in 2012 ($p \leq 0.006$) (Table 2-5). Blum (2009) noted that increased *HI* in grain sorghum is directly related to increased WUE due to optimal distribution of available water as evident under MDI and FI. Decreased *HI* and seed mass under DI in 2012 are a factor of water stress and aborted seeds during anthesis as also reported by Crauford and Peacock (1993).

Water use efficiencies are typically lower under drought stress so it is not surprising that WUE of DI sorghum was significantly lower than the WUE of FI sorghum in 2010 and 2012 ($p \leq 0.001$); however, the WUE of MDI was only significantly lower than that of FI in 2012 ($p = 0.001$) demonstrating that limiting water did not reduce WUE in two of the three years (Fig. 2-8). As observed by Hsiao and Acevedo (1974), reductions in WUE can occur when water resources are not optimized under deficit irrigation. In 2011, there were not any differences in WUE among all irrigation strategies ($p = 0.647$) although yield variability among the replications was large during this year.

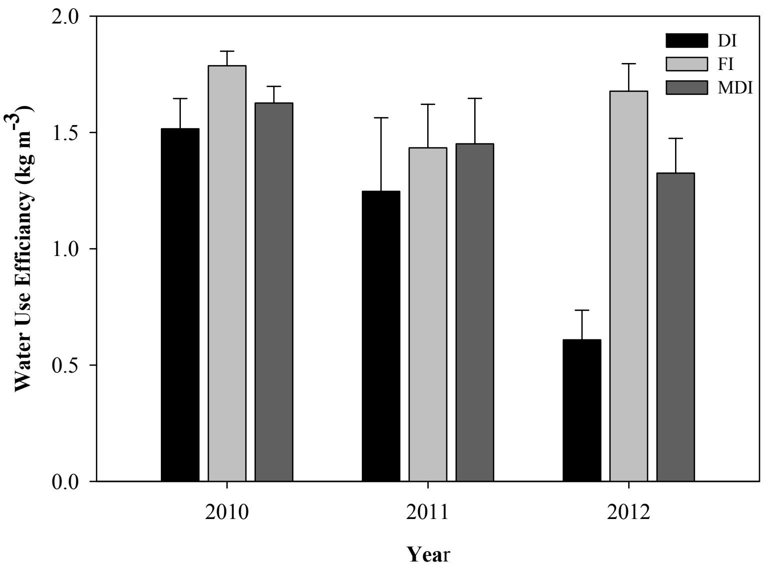

Figure 2-8. Water use efficiency with bars indicating plus 95% confidence for all years and full irrigation (FI), managed deficit irrigation (MDI), and deficit irrigation (DI) treatments.

The three-year mean water use of MDI was only 29 mm greater than the three-year water use of DI. Increased water use under MDI was accompanied by a 1.6 Mg ha^{-1} greater mean yield. For the incremental water use and yield under MDI compared with DI, this translates into a mean WUE of 3.06 to 9.84 kg m^{-3} for these three years. Throughout the three-year period, the incremental yield increase per unit of additional water used under FI compared with MDI resulted in a smaller mean WUE (1.9 kg m^{-3}). As shown by Howell et al. (2007), when precipitation is below average, DI poses the greatest reduction in WUE and greatest risk of yield reductions due to the collective effect of reduced irrigation and precipitation. In this study, the 29 mm increase in water use under MDI between growing point differentiation and half-bloom compared with DI lessened the effect of negligible precipitation in 2012 on yield. Consequently, concentrating water during the critical growth periods between growing point differentiation and half-bloom can improve WUE, which is especially important under conditions of limited water due to reduced well capacity and/or reduced precipitation.

II.4 CONCLUSIONS

In all years, yield under FI was significantly greater than yield under DI and MDI. While a greater yield response was achieved under MDI compared with DI in all years, this was only significant in 2010 and 2012. The response of SPP to irrigation treatments mirrored grain yield and was greatest under FI in all years. Elimination of an early season irrigation event under MDI, during the vegetative stage, provided the opportunity to increase irrigation during the reproductive stages from growing point differentiation to half- bloom. Increased irrigation during this period resulted in significantly greater SPP under MDI compared to DI in 2011 and 2012. The FAO-56 predicted water use underestimated FI water use (*ET*) in all years of the study prior to growing point differentiation possibly reflecting large soil water evaporation losses under sparse canopy cover. Under DI, decreased irrigation and thus *ET* between growing point differentiation and maturity likely resulted in aborted ovules and/or decreased pollination. Seed mass was significantly different among irrigation treatments; however, there were no significant correlations between seed mass and yield.

The WUE of DI sorghum was significantly lower than the WUE of FI in 2010 and 2012; however, the WUE of MDI was only significantly lower than that of FI in 2012. Consequently, limiting water under MDI did not reduce the WUE in two of the three study years. While FI provides the greatest opportunity to reduce production risks through increased yield, if irrigation water is limiting, MDI provides less risk than DI due to its ability to maintain yield and WUE as was evident in 2012. As such, concentrating irrigation water during the critical growth stage resulted in a greater yield compared with irrigation scheduling based on a fraction of full irrigation.

CHAPTER III

EFFECTS OF IRRIGATION LEVEL AND TIMING ON PROFILE SOIL WATER USE BY GRAIN SORGHUM

III.1 INTRODUCTION

Development and evaluation of sustainable and efficient irrigation strategies is a priority for producers faced with water shortages resulting from aquifer depletion, reduced base flows in streams and rivers, and reallocation of water to non-agricultural sectors. Because irrigation can be used to mitigate year-to-year variability associated with rain-limited production systems, it is necessary to promote sound management strategies to conserve water resources. Globally, agriculture accounts for approximately 70% of water use (Gurian-Sherman, D., 2012; Calzadilla et al., 2010). On the Texas High Plains, irrigation water is principally pumped from the Ogallala Aquifer. While the Ogallala Aquifer is the largest aquifer in the United States, underlying 450,000 km^2 of the western side of the Great Plains, stretching from South Dakota to Texas, groundwater withdrawals in Texas, primarily due to irrigation, greatly exceed recharge, which has been estimated to be range from 0.02 to 111.0 mm yr^{-1} across the High Plains region; although, recharge is much lower across the central and southern High Plains ranging from 0.02 to 54.1 mm yr^{-1} (Gurdak and Roe, 2009). To conserve water for future use, regional water districts are imposing restrictions on the amount of water that can be pumped. Accordingly, producers are considering irrigation strategies to optimize water use and minimize production risks associated with reduced pumping. As regional irrigation becomes increasingly limited, it is essential that the effects of restricted availability of irrigation water on production are understood. Under limited pumping scenarios, it is likely that producers may not be able to achieve maximum crop yield on all formerly irrigated lands. However, implementation of management strategies that maximize water use efficiencies (WUE) of irrigation water, stored soil water, and precipitation may potentially minimize production risks while sustaining a water supply for future irrigated production and other uses.

A promising management strategy for improving efficiencies of irrigation water use involves supplying water at an amount less than could be used by the crop under full irrigation where water is non-limiting with respect to yield (full irrigation). Deficit irrigation is generally implemented such that the water is applied at a fixed fraction of full irrigation. However, levels of deficit irrigation may be managed within the growing season whereby greater applications occur at critical growth stages if required to optimize the use of irrigation water and precipitation. Incorporation of a managed deficit irrigation strategy coupled with drought tolerant crops enables the strategic allocation of available water for yield maximization and optimal water use under water-limited conditions.

Drought tolerant crops such as grain sorghum have the potential to minimize production risks due to inherent physiological adaptations such as osmotic adjustment, which allow the crop to withstand short-term water deficits. Therefore, under limited water, the greatest yield may be achieved through management of the temporal patterns of water use. Howell and Hiller (1975) concluded that the yield response of grain sorghum to irrigation was not correlated to seasonal *ET*; yield responses were dependent on the timing of the *ET* deficit.

The study objective was to compare the influence of irrigation strategies on water use throughout the season with respect to growth stages and soil water depletion with respect to depth. It was hypothesized that less frequent and lower irrigation amounts would stimulate greater root elongation and greater uptake of soil water deeper in the profile, and increasing irrigation level from growing point differentiation to half-bloom at expense of less water during vegetative stage would improve WUE.

III.2 APPROACH AND RESEARCH PROCEDURES

Research was conducted at the USDA-Agricultural Research Service, Conservation and Production Research Laboratory, Bushland, Texas, USA (35°11′N, 102°5′W; 1170 m elevation) for three growing seasons from 2010 to 2012. Twelve experimental plots (15- by 109-m) in a randomized complete block design were established on a 180- by 109-m field on Pullman clay loam (Fine, mixed, superactive, thermic Torrertic Paleustoll) with < 1% slope. Soil texture and measured water retention characteristics are included in Appendix B and C, respectively. Soil texture was determined using the hydrometer method described by Gee and Bauder (1986). Soil water retention characteristics of the Pullman soil were determined using a pressure plate extractor (Klute, 1986). A mid-season grain sorghum cultivar (DeKalb DKS44-20) was evaluated under four irrigation treatments: full irrigation (FI), deficit irrigation (DI), managed deficit irrigation (MDI), and non-irrigated (NI). Each treatment was replicated three times. Soil water contents were determined using a neutron moisture gage (model 503DR, InstroTek, Inc., Raleigh, NC) from 0.1- to 2.3-m depth in 0.2-m increments at weekly intervals throughout the growing season at two locations in each of the 12 experimental plots. An additional four access tubes were located in MDI plots for a detailed sub-study of MDI with time-domain reflectometry. The neutron moisture gage was previously field calibrated for the Pullman soil for the A, Bt and Btk horizons (Evett and Steiner, 1995) with 1.0% accuracy (Appendix A).

The crop rooting zone used for evaluation of soil water use was defined as the upper 1.6 m for all treatments and years. Drainage flux at 2.2 m using previously determined water retention measurements (Moroke, 2002; Musick and Sletten, 1966) and conductivity estimates for similar calcic horizons (Baumhardt and Lascano, 1993) averaged ~16 mm and was not significantly different among treatments and not significantly different from zero in all three years ($p \geq 0.249$). In addition, maximum variations in water contents at 1.6- to 2.2-m depth were < 0.026 $m^3 m^{-3}$ from emergence to physiological maturity and the associated changes in storage were not significantly different from zero in all three years ($p \geq 0.210$). Negligible change in storage from 1.6-

to 2.2-m and the lack of drainage below 2.2 m therefore suggests that rooting depth and soil water use was restricted to the upper 1.6 m of the profile. When evaluating soil water content data, soil water that exceeded field capacity (-33 kPa) was assumed available due to the slow drainage rate in this soil.

Scheduling of FI was based on weekly measurements of precipitation plus change in stored soil water within the rooting zone (0 to 1.6m). Irrigation was applied at a depth of 25 to 32 mm to the FI treatment when stored soil water fell below a set managed allowable depletion (*MAD*) of 50% of potential plant available water (*PPAW*) in the rooting zone. *PPAW* was defined as the difference between depth averaged water contents at -33 kPa (0.328 $m^3 m^{-3}$) and -1.5 MPa (0.197 $m^3 m^{-3}$) measured in 0.2-m increments throughout the root zone (0 to 1.6 m) based on water retention measurements of Musick and Sletten (1966). Calculated *PPAW* was 210 mm [(0.328 $m^3 m^{-3}$ – 0.197 $m^3 m^{-3}$) × 1600 mm] for this soil. The DI treatment was scheduled at 50% the amount of FI and applied at application depths similar to the FI treatment but less frequently. Scheduling of MDI was based on a fraction of the cumulative amount of FI and varied with growth stage. During the vegetative growth stage, one or two irrigations were omitted from MDI compared with DI, such that applications amounts for MDI were less than 50% of the FI treatment for that stage. From panicle differentiation to half-bloom (approximately 35 to 70 days after planting for DeKalb DKS44-20 at the site), irrigations for MDI were scheduled at 75% the amount of FI. From half-bloom to physiological maturity, irrigations for MDI were scheduled at 50% of FI. As with DI, irrigation of the crop under MDI was applied at similar application depths of the FI treatment but less frequently.

Irrigation was applied with a three-span, lateral-move sprinkler system (Model 6000, Valmont Irrigation, Valley, NE) with drop hoses positioned at 1.5 m spacing and nozzles at 0.5 m above the ground surface. Low drift nozzles (No. 15; 0.32 L s^{-1}; Senninger Irrigation, Inc., Clermont, FL) were equipped with convex-medium grooved spray pads and 69 kPa pressure regulators.

Prior to initiation of experimental plots in 2010, the research field was deep-tilled using a para-plow in the fall of 2009 to partially disrupt a plow pan that developed from previous management. Research plots were deep chiseled each fall following harvest using a chisel-chopper drag plow (BJM Sales and Service, Hereford, TX). Plots were sweep-tilled twice each spring for weed control and seedbed preparation at a depth of approximately 0.13 m using a three-blade, 4.5-m sweep plow with one 1.5-m wide center blade and two exterior 1.8-m wide blades.

Experimental plots were sampled and analyzed for fertility requirements in April of each experimental year for a grain yield goal of 11 Mg ha^{-1} under irrigation and 4 Mg ha^{-1} under non-irrigated treatments. Based on these analyses, average nitrogen and phosphorus (P_2O_5) application rates were 180 to 193 kg ha^{-1} N and 29 to 42 kg ha^{-1} P_2O_5. Each May, ammonium polyphosphate (10-34-0) and urea ammonium-nitrate (32-0-0) were mixed and knifed-in (62 kg ha^{-1} N and 29 kg ha^{-1} P_2O_5) as a pre-plant fertilizer across all irrigated plots to meet the crop total phosphorus and partial nitrogen requirements. Remaining nitrogen requirements were applied through injection of 32-0-0 into irrigation water through the sprinkler at the 10-leaf stage. The sorghum seed was planted on 0.76-m row spacing using a Max-Emerge vacuum planter (John Deere, East Moline, IL) at seeding densities of 161,000 ha^{-1} in 2010 and 2011 and 173,100 ha^{-1} in 2012. Bicep II Magnum (Atrazine plus S-metolachlor; Syngenta Crop Protection, LLC) was sprayed as a pre-emergent to control in-season weeds.

Micrometerological variables were monitored using a datalogger (model CR23X, Campbell Scientific, Inc., Logan, UT) and environmental instrumentation located centrally within the experimental field. Measurements were recorded at 0.25-h intervals and included ambient air temperature and relative humidity (model HMP45C Temperature and Humidity Probe, Vaisala Inc., Helsinki, Finland), wind velocity (model 014A wind sensor, MET-ONE Instruments, Inc, Grants Pass, OR), and total global irradiance (model LI-200SA pyranometer, Li-Cor Biosciences, Lincoln, NE) all at 2 m above the surface. Precipitation was measured using a tipping bucket rain gage (TE525M, Texas Electronics, Dallas, TX) and incoming and reflected short and longwave radiation in 2010 and 2012 (models CM14 albedometer and CGR3 pyrgeometer, Kipp and Zonen, Delft, Netherlands), and net radiation (model Q*7.1 Net Radiometer, REBS, Bellevue, WA) were measured at 0.5 to 1.0 m above the canopy. Reference evapotranspiration (ET_0) was calculated from monitored variables using the ASCE standardized reference evapotranspiration equation at hourly, sub-daily hourly intervals (Allen et al., 2005).

Using weekly neutron gage measurements, crop evapotranspiration (ET) was estimated using a water balance approach (Hulugalle and Lal, 1986; Evett et al., 1993):

$$ET = P + I - \Delta S - R - D \qquad (1)$$

where P is precipitation, I is irrigation, ΔS is the change in stored water from 0 to 1.6 m, R is net runoff, and D is drainage below the root zone. In this study, R and D were assumed negligible.

Grain and aboveground biomass were sampled at physiological maturity from three 9-m^2 subsamples of each plot. Processing of yield and yield component samples are described in Chapter II. Water use efficiency (WUE, kg m^{-3}) was calculated as the ratio of grain yield (0.13 kg kg^{-1} or 13% wet-basis moisture content, kg m^{-2}) to ET (m).

Green leaf area index (LAI) was determined by sampling three representative sorghum plants from each of three 0.76 m^2 subplots within each experimental plot. Senesced leaved were removed, and green leaf area was measured using a leaf area meter (model LI-3100, LICOR, Inc., Lincoln, NE). Green leaf area index was calculated for each subplot by multiplying the mean leaf area per plant by the plant population and dividing this result by the subplot area. Maximum rooting depth was measured at three locations in each plot using the core-break method (Böhm, 1979). Only roots exhibiting elasticity (new roots) were considered when determining maximum rooting depth in 0.34-m diameter × 2.0-m length cores.

Statistical analysis was completed using the general linear procedure (SAS Institute, 2009) to test for significant irrigation treatment effects on dependent variables yield, yield components, seasonal water use and water use efficiency. In most cases, irrigation effects were examined separately within each year because of significant year ×

irrigation interactions. Because NI failed in 2011 and 2012 due to extreme environmental conditions and crop failure in two of the three seasons, the NI treatment was omitted in all statistical tests. Confidence intervals and adjusted least significant differences for multiple comparisons were determined using Tukey's HSD. A paired comparison procedure (SAS Institute, 2009) was used to test for statistical differences between soil water contents at planting and maturity at all depth increments. Effects and comparisons were declared significant when below $\alpha = 0.05$ probability level.

III.3 RESULTS AND DISCUSSION

III.3.1 Grain Yield, Water Use and Leaf Area Index

Mean grain yield from FI treatments exceeded yields of MDI and DI treatments in all three years ($p < 0.001$) (Chapter II, Table 2-5). However, mean grain yields of MDI were greater than yields of DI in all years, although only significantly greater ($p \leq 0.001$) in two of the three years (2010 and 2012). Compared with DI and MDI, WUE of FI was only significantly greater in 2012. In 2010 and 2011, there were not any significant differences between WUE of FI and MDI ($p \geq 0.063$), and there were not any significant differences between WUE of DI and MDI ($p \geq 0.201$) (Chapter II, Fig. 2-8).

Grain yield from all irrigation treatments and years was strongly correlated to cumulative crop evapotranspiration (*ET*) (r^2=0.95 to 0.97). However, water use during critical growth stages exhibited distinct characteristics for each of the three years (Fig. 3-1). Seasonal water use in 2010 was skewed by early season precipitation, which mitigated the effect of reduced irrigation under the MDI treatment during the crop vegetative stage (emergence to growing point differentiation). Under FI, in 2010, water use from half-bloom to hard dough was approximately 100 mm greater than water use between growing point differentiation and half-bloom (Fig. 3-1). While FI received additional water during grain fill in 2010, seed mass of FI was not significantly greater than seed mass of MDI ($p = 0.297$). There were significantly greater seeds panicle^{-1} under FI ($p < 0.001$) in comparison to DI and MDI (Chapter II, Table 2-6). Water was allocated among the FI crop's significantly greater number of seeds per panicle rather than increasing seed mass. Conversely, water use under MDI and DI from half-bloom to hard dough was less than or equal to water use from growing point differentiation to half-bloom. Water use in 2011 under all treatments was greater from growing point differentiation to half-bloom due to greater ET_0 compared with 2010 and 2012 (Fig. 3-1). Total water use from growing point differentiation to half-bloom in 2012 was similar to water use in the same period in 2010, but seed number was significantly less in 2012 for all treatments (p = 0.001). This may have resulted from reduced water towards the end of bloom in 2012 and associated water stress resulting in abortion of ovules. Depressed seed number was likely responsible for lower grain yields in 2012 compared with 2010 and 2011.

The magnitude and temporal variation of *LAI* varied among irrigation treatments and years (Fig. 3-2). In 2010, there were no differences (p = 0.159) in *LAI* among irrigation treatments until after half-bloom. However, maximum *LAI* of FI and deficit irrigated treatments were attained at different development stages. Maximum *LAI* for deficit irrigated treatments was achieved at half-bloom (day 222) while maximum *LAI* for FI was achieved at Soft Dough. As the crop began to senesce during grain fill, significant differences in *LAI* between FI and deficit irrigated treatments (p = 0.001) were realized. Hsiao (1974) demonstrated that leaf senescence during grain fill decreases the assimilation of photosynthate to the grain and thereby reduces grain yield. In 2011 and 2012, *LAI* was significantly different (p = 0.001) between the FI treatment and both deficit irrigation treatments throughout the growing season except at boot on day 205 in 2012. At this stage, there were no differences among 2012 irrigation treatments (p = 0.138). However, *LAI* of the DI treatment dropped below that of MDI during the critical reproductive period likely because of the greater water deficit under DI. In contrast to 2010 and 2011, *LAI* senesced following boot in 2012 under all irrigation treatments (Fig. 3-2), which is suggestive of some degree of water stress or drought induced senescence at all irrigation levels.

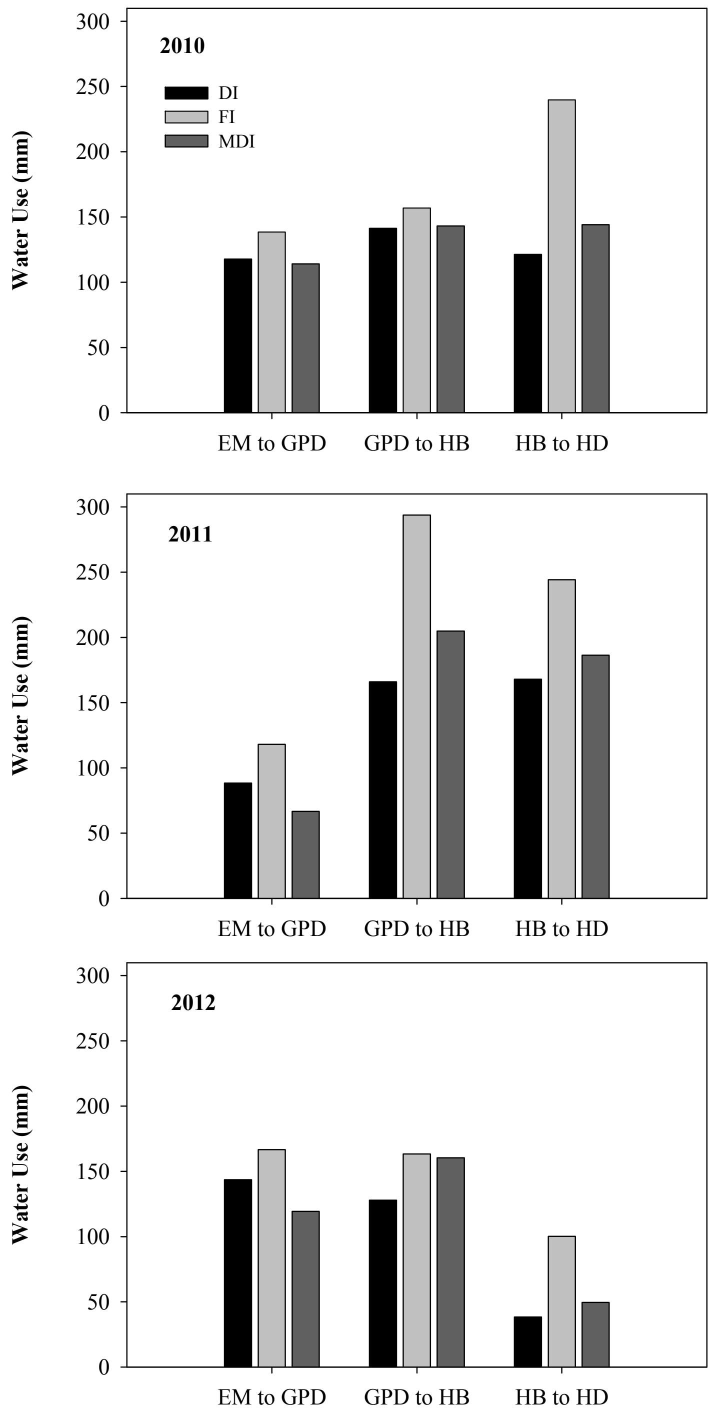

Figure 3-1. Water use within specific growth stages. (EM = emergence, GPD = growing point differentiation, HB = half-bloom, HD = hard dough)

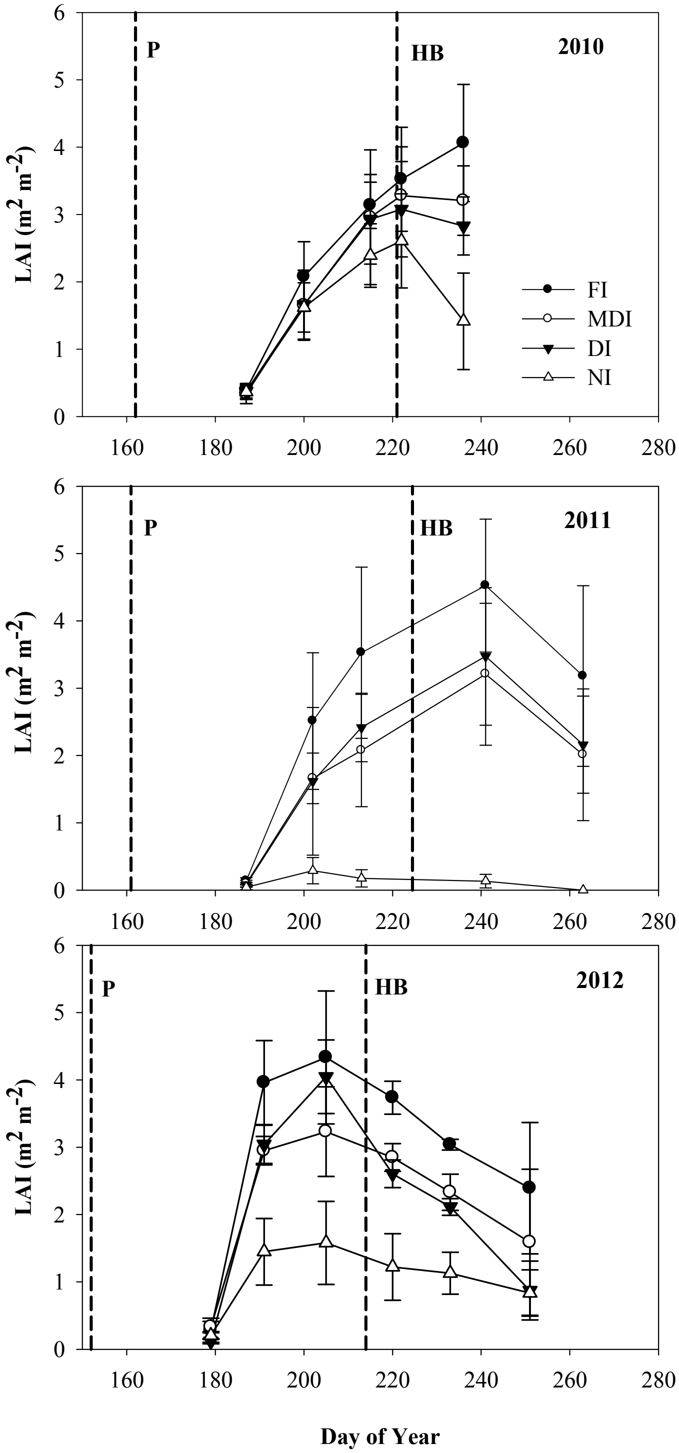

Figure 3-2. Leaf area index for all growing seasons (E = Emergence and HB = Half-Bloom) and full irrigation (FI), managed deficit irrigation (MDI), and deficit irrigation (DI) treatments.

III.3.2 Root Zone Plant Available Water

Potential plant available water (*PPAW*) for the Pullman soil integrated to 1.6 m was 208 mm with managed allowed depletion being 104 mm or 50% *PPAW*. To implement the deficit irrigation treatments, it was necessary that the FI treatment be maintained at or above 50% *PPAW*. In 2010 and 2012, *PAW* under FI exceeded or equaled 50% *PPAW*, except for a short duration as the crop reached physiological maturity in 2012 (Fig. 3-3). In 2011, *PAW* declined to as low as 89 mm ± 17 s.d. (43% *PPAW*) under FI during half-bloom. During this period, maintenance of *PAW* at or above 50% *PPAW* through surface irrigation was difficult due to extremely high ET_0 and associated crop water use combined with low pre-plant soil water contents. Under full irrigation, mean *PAW* at emergence was greatest in 2012 (191 mm) compared with 2010 and 2011 (146 and 96 mm greater than 2010) (Table 3-1). Despite having an initial water content and *PAW* greater than 50% *PPAW* throughout the growing season, cumulative water use and grain yield were both lower under FI in 2012 compared with 2010 and 2011.

Table 3-1. Plant available water at critical growth stages for and full irrigation (FI), managed deficit irrigation (MDI), and deficit irrigation (DI) treatments.

		Plant Available Water					
Plot	**Year**	**Emergence**	**Stdev**	**Half-Bloom**	**Stdev**	**Hard Dough**	**Stdev**
		------------------------------mm------------------------------					
DI	2010	158	26	96	19	91	16
FI	2010	146	8	141	13	118	12
MDI	2010	155	20	114	19	99	19
DI	2011	91	31	72	19	63	28
FI	2011	96	19	89	17	110	36
MDI	2011	91	25	91	19	82	31
DI	2012	148	33	51	20	36	17
FI	2012	191	18	99	22	100	16
MDI	2012	168	31	62	26	55	26

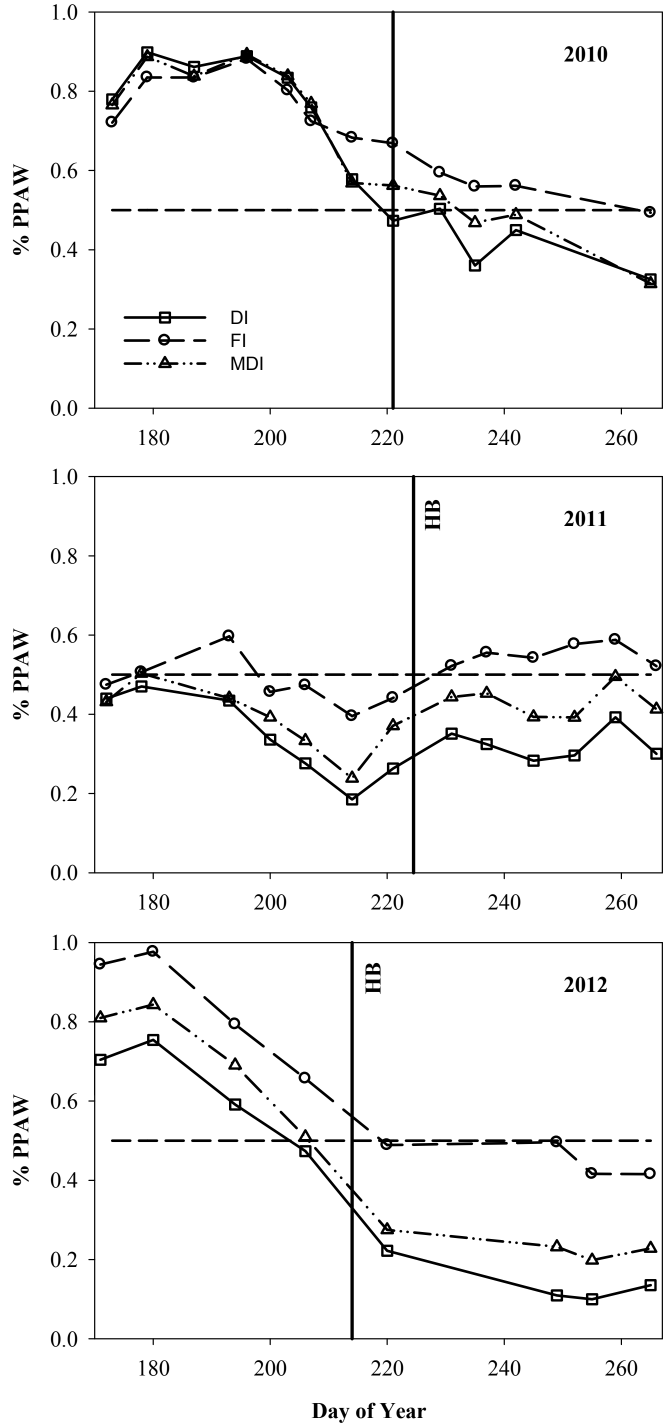

Figure 3-3. Plant available water in the root zone (0 to 1.6 m) as a fraction of PPAW for full irrigation (FI), managed deficit irrigation (MDI), and deficit irrigation (DI) treatments throughout the growing season for all years (HB=Half-Bloom).

III.3.3 Seasonal Changes in Soil Water Storage and Rooting Depth

Change in soil water storage at the 1.4- to 1.8-m and 1.8- to 2.2-m depth increments in all years from emergence to half-bloom was not significantly different from zero for all irrigation treatments (Figs. 3-4 to 3-6). Following half-bloom, mean water contents at the 1.4 to 1.8 depth increment began to decline under deficit irrigation treatments in 2010 and 2012 (Fig. 3-4 and 3-6), which is indicative of plant uptake as drainage at 2.2 was found to be insignificant. However, changes in soil water contents from half-bloom to physiological maturity at the 1.4 to 1.8 m depth, which averaged ~5 mm, were not significantly different from zero ($p \geq 0.146$). In 2010 and 2012, decline in soil water contents from half-bloom to physiological maturity at 1.0 to 1.4 m was similar among all treatments and reflective of water uptake at this depth increment. The mean change in water contents was -12 and -11 mm in 2010 and 2012, respectively and significantly different from zero ($p \leq 0.003$). In 2011, there were not any significant changes in soil water below 0.6 m for all irrigation treatments from half-bloom to maturity throughout the growing season ($p \geq 0.153$) (Fig. 3-5).

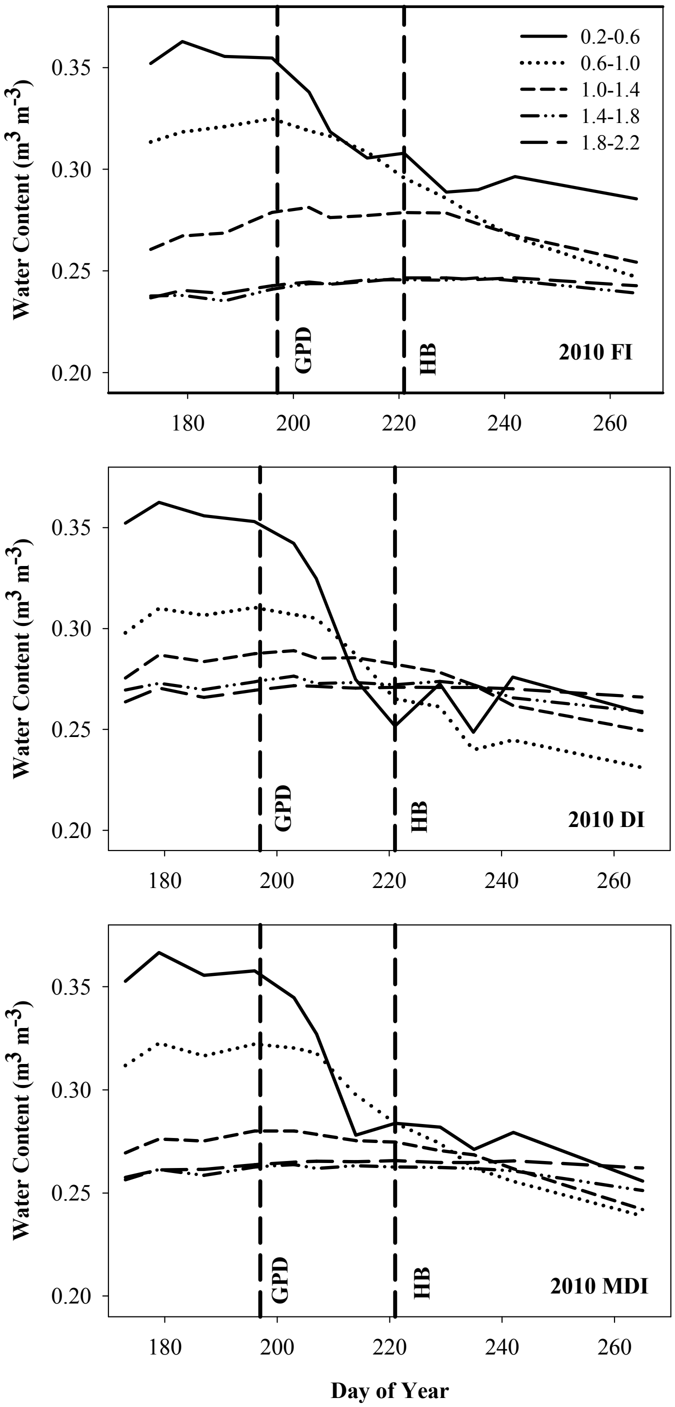

Figure 3-4. Soil water contents at selected depth increments for full irrigation (FI), managed deficit irrigation (MDI), and deficit irrigation (DI) treatments in 2010 (GPD = growing point differentiation and HB = half-bloom).

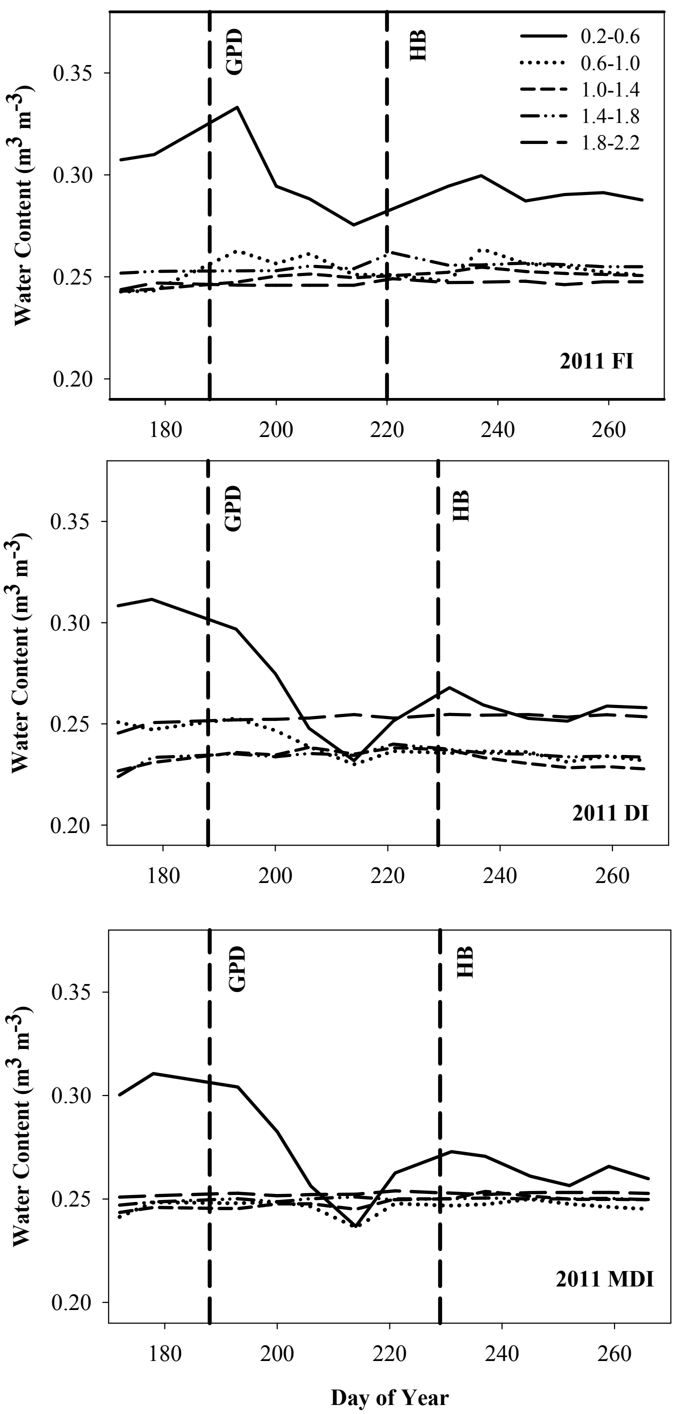

Figure 3-5. Soil water contents at selected depth increments for full irrigation (FI), managed deficit irrigation (MDI), and deficit irrigation (DI) treatments in 2011 (GPD = growing point differentiation and HB = half-bloom).

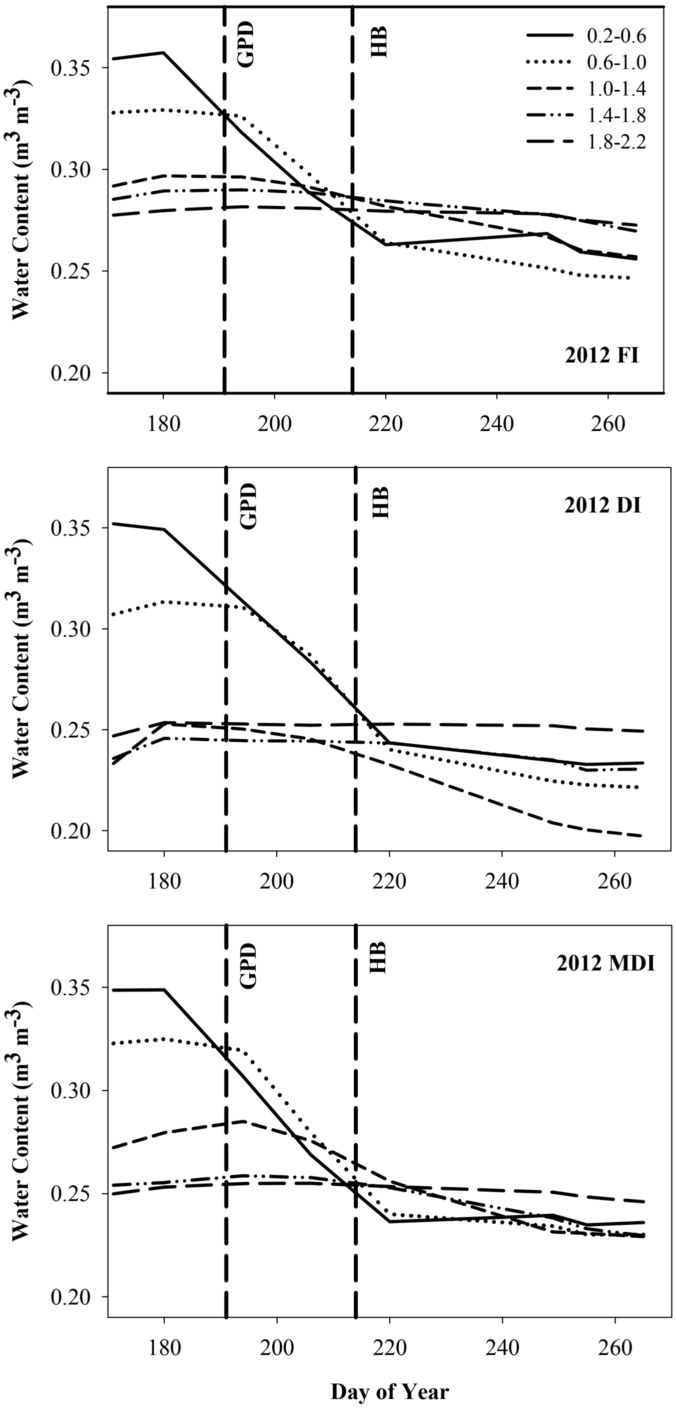

Figure 3-6. Soil water contents at selected depth increments for full irrigation (FI), managed deficit irrigation (MDI), and deficit irrigation (DI) treatments in 2012 (GPD = growing point differentiation and HB = half-bloom).

Maximum rooting depths evaluated from soil cores at growing point differentiation and physiological maturity (Table 3-2) were significantly influenced by cropping year ($p < 0.001$). Maximum rooting depth was greater in 2010 compared with 2011 likely because of limited plant available water below 0.6 m during 2011. In 2010 and 2012, there was no significant irrigation treatment effect on maximum rooting depth at all growth stages ($p \geq 0.181$). However, in 2011, there was a significant irrigation treatment effect on maximum rooting depth at growing point differentiation ($p = 0.034$) and nearly a significant treatment effect at physiological maturity ($p = 0.065$). During 2011, fully irrigated plots tended to have the greatest rooting depths (Table 3-2). An equal or greater rooting depth under FI was unanticipated as it was hypothesized that rooting depth would be greater under water deficits to compensate for reduced soil water contents near the surface.

Table 3-2. Maximum observed rooting depth at growing point differentiation (GPD) and maturity for full irrigation (FI), managed deficit irrigation (MDI), and deficit irrigation (DI) treatments (NA=Not Available).

Year	Developmental Stage	DI	FI	MDI	LSD§
		----------------------m----------------------			
2010	**GPD**	0.44	0.48	0.50	0.20
	Maturity	1.30	1.29	1.35	0.18
2011	**GPD**	0.20	0.20	0.18	0.08
	Maturity	0.76	0.94	0.85	0.18
2012	**GPD**	0.71	0.64	0.66	0.10
	Maturity	NA[ǂ]	NA	NA	-

[ǂ]NA – Not available
§ Adjusted least significant difference based on Tukey's Honest Significant Difference test.

III.3.4 Soil Water Contents by Depth in Relation to Plant Available Water

In the previous sections, *PAW* was presented and discussed as a quantity integrated throughout the profile (0- to1.6-m) without distinguishing how the available water in the profile was distributed with depth. Soil water contents by depth in relation to soil water contents at field capacity, permanent wilting point, and 50% of potential plant available water with depth (*PPAW*(*z*)) are plotted for all years and irrigation treatments (Figs. 3-7 to 3-9). As previously discussed, FI was based on managed allowed depletion such that soil water contents maintained above 50% *PPAW* were averaged throughout the entire soil profile to 1.6 m.

Under full irrigation in 2012, water contents were greater than 50% *PPAW*(*z*) until half-bloom within the entire profile (0 to 1.6 m) (Fig. 3-9). At half-bloom, mean water contents fell below 50% *PPAW*(*z*) to ~0.25 m^3 m^{-3} in the upper profile (0- to 0.8-m). However, mean water contents at depths from 0.8- to 1.6- m were 0.28 m^3 m^{-3} and greater than *PPAW*(*z*) at half-bloom (Fig. 3-9), which resulted in the depth averaged *PPAW* mean water content for the "root zone" to be maintained at 50% *PPAW* (0.265 m^3 m^{-3}) or above (Fig. 3-3). Despite the availability of water deeper in the profile, only 15 mm was utilized from half-bloom to hard dough by the fully irrigated crop in 2012 below 0.6 m. In contrast to 2012, water contents above 0.6 m were maintained above 50% *PPAW*(*z*) under full irrigation from emergence to hard dough in 2011. In 2010, water contents were maintained above 50% *PPAW*(*z*) throughout the growing season above 1.2 m. There was evidence of root extension to deeper depths under full irrigation (Fig. 3-6; Table 3-3) in 2012; however, from half-bloom to physiological maturity, a relatively low ET (compared with FI in 2010 and 2011) (Fig. 3-1) and a declining *LAI* (Fig. 3-2) suggest that the crop was water stressed. These observations suggest that water deeper in the profile in 2012 was not available to the degree it was nearer the surface. Although there was evidence of root uptake to 1.4 m under FI in 2012 (Fig 3-6; Fig. 3-9) root density at these depths were likely insufficient to access plant available water from the entire soil volume (e.g. Moroke et al., 2005). Consequently, (based on the concepts of radial water flow to roots introduced by Gardner, 1964) water contents surrounding the roots deeper the profile would be lower than water contents measured by the neutron moisture gage. In this respect, neutron moisture gages may not give an accurate representation of water contents near the root, the corresponding water stress experienced by the crop, and hence, irrigation requirements when root length density is sparse. These results are contrary to current concepts that root extension continues at low water potentials in order to utilize water at deeper depths (Assefa et al., 2010; Ober and Sharp, 2007). Plant response at low soil water potential is a reaction to the production of the plant hormone, abscisic acid, which induces stomatal closure in the leaves and increased root growth. Evaluation of root growth in corn has revealed that mutated cultivars deficient in abscisic acid continue shoot growth in lieu of root growth to sustain water uptake under drought, which enhances water stress (Chavez et al., 2003; Sharp et al., 1994).

In 2010, soil water contents within the rooting zone (0 to 1.6 m) were > 50% $PPAW(z)$ at emergence under the deficit irrigation treatments (Fig. 3-7); however, in 2012, soil water contents were < 50% $PPAW$ below 1.2 m at planting (Fig. 3-9). In 2010, soil water contents fell below 50% $PPAW(z)$ under DI at half-bloom in the 0- to 0.8-m increment while in 2012, soil water contents in the entire root zone (0 to 1.6 m) were < 50% $PPAW$. Like FI, water contents in 2010 under MDI remained above 50% $PPAW(z)$ at half-bloom a result of increased irrigation frequency during the critical growth period (Figs. 3-3 and 3-7). By hard dough soil, water contents were ≤ 50% $PPAW$ at all depth increments under DI and MDI in 2010 and 2012 (Figs. 3-7).

Despite initial water contents averaging 42% of $PPAW$ in 2011 at the 0.6- to 1.0-m depth increment under all irrigation treatments, water contents in this zone did not significantly change throughout the entire season suggesting that nearly all of the root water uptake was confined to above 0.6 m (Fig. 3-5). Sub-optimal yields under FI were likely not realized in 2011 because irrigation and precipitation provided nearly all of the water requirements for the crop (Table 3-3). WUE was relatively low in 2011 because of the high seasonal ET_0 and corresponding greater water use. Root extension and subsequent water uptake deeper in the profile may require soil water contents to be greater than approximately 50% *PPAW* under conditions when the sorghum can access near surface soil water at relatively low potentials. In this study, reduced irrigation and corresponding greater water potentials near the surface under deficit strategies was insufficient to generate compensatory uptake deeper in the horizon in 2011(Fig. 3-8). Some evidence of uptake was observed in 2010 and 2012 as detected by the decline in water content within the 1.0- to 1.4-m depth increment under DI and MDI (13.1 to 12.5 mm, respectively) (Figs. 3-4 and 3-6); however, this was only marginally greater than declines under FI (8.8 mm) (Fig. 3-5). At this depth increment, the changes occurred under conditions where PAW was largely greater than 50% $PPAW(z)$ (0.265 m^3 m^{-3}) at half-bloom. Consequently, there was also little evidence of compensatory uptake under deficit irrigation strategies 2010 and 2012. However, water uptake deeper in the profile was small in magnitude (<5.7 mm) at 1.4 to 1.8 m depth from growing point differentiation to hard dough in 2010 and 2012, and insufficient to significantly influence grain yield.

Table 3-3. Cumulative growing season crop *ET* and individual components (ΔS, precipitation and irrigation) for full irrigation (FI), managed deficit irrigation (MDI), and deficit irrigation (DI) treatments.

Plot	Year	ΔS	Precip.	Irrigation	*ET*
		----------------------	--mm--	----------------------	
DI	2010	-62.1	180.5	132.8	375.4
FI	2010	-10.6	180.5	322.3	513.4
MDI	2010	-41.3	180.5	164.6	386.3
DI	2011	-17.9	61.2	332.0	411.1
FI	2011	-6.7	61.2	608.6	676.5
MDI	2011	2.6	61.2	388.6	447.3
DI	2012	-99.9	34.5	152.4	286.8
FI	2012	-92.3	34.5	304.8	431.6
MDI	2012	-108.4	34.5	177.8	320.7

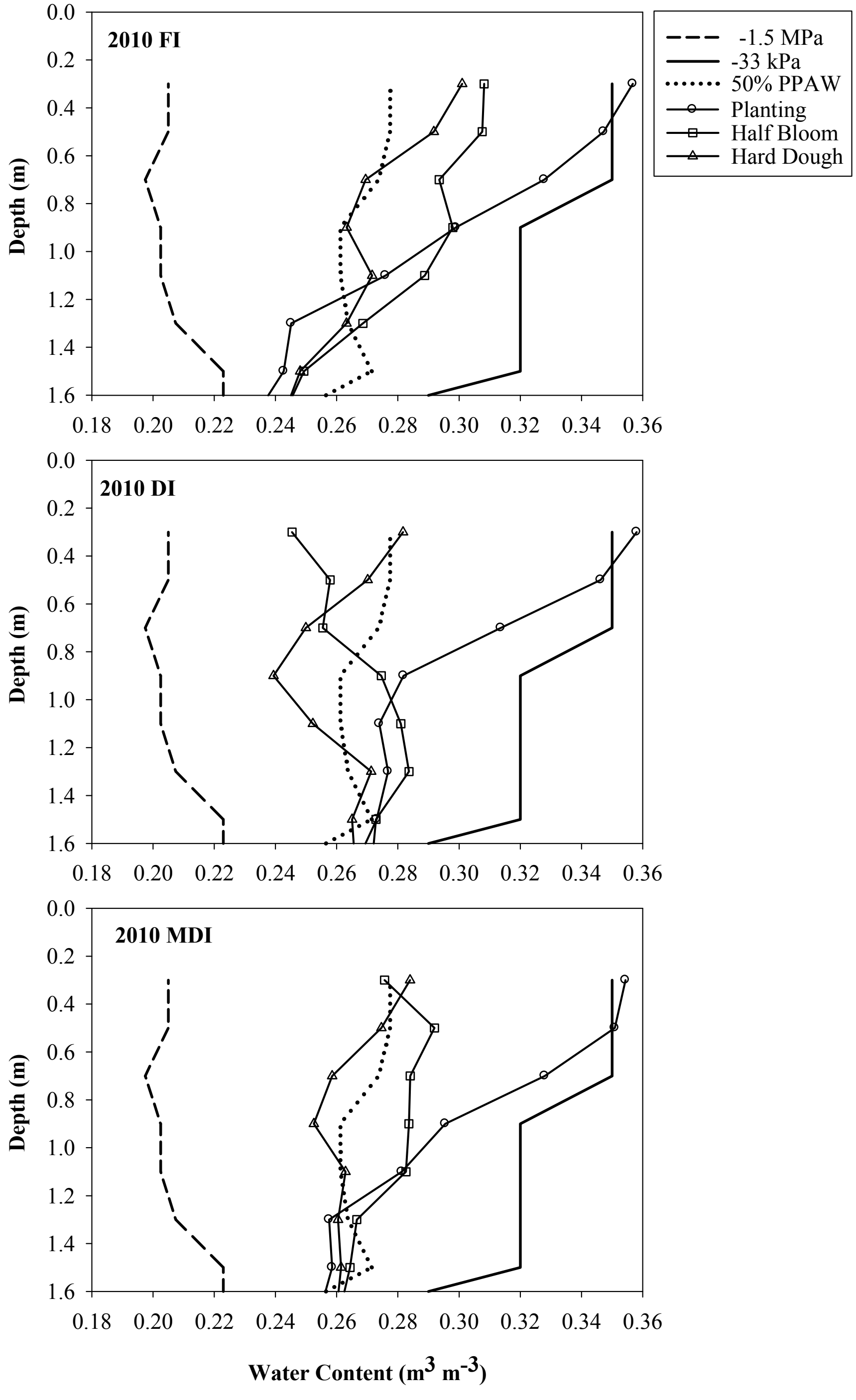

Figure 3-7. Soil water contents by depth increments in relation to water content at field capacity (-33 kPa), wilting point (-1.5 MPa) and 50% potential plant available water [50% *PPAW*(*z*)] in 2010 for full irrigation (FI), managed deficit irrigation (MDI), and deficit irrigation (DI) treatments.

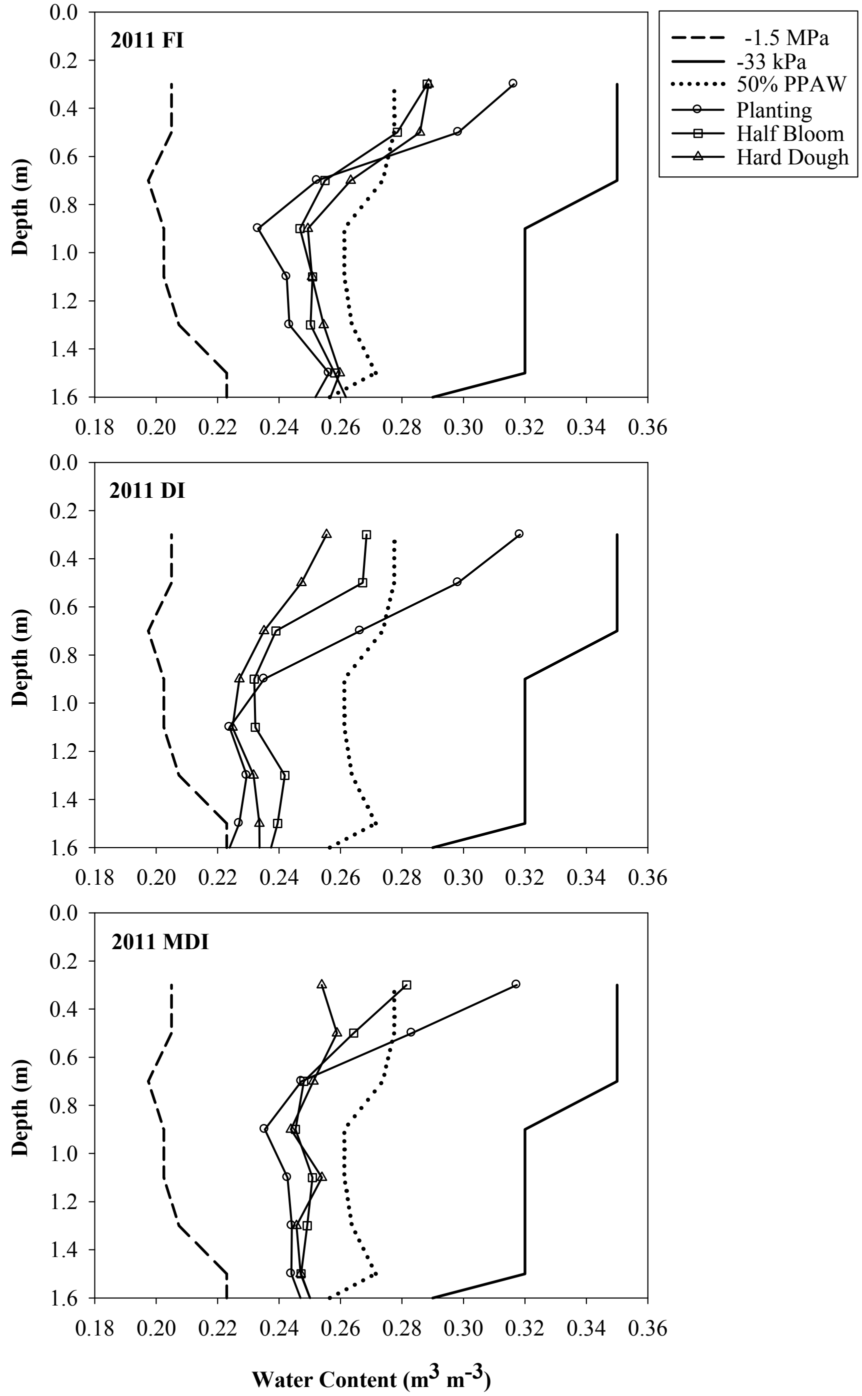

Figure 3-8. Soil water contents by depth increments in relation to water content at field capacity (-33 kPa), wilting point (-1.5 MPa) and 50% potential plant available water [50% *PPAW*(*z*)] in 2011 for full irrigation (FI), managed deficit irrigation (MDI), and deficit irrigation (DI) treatments.

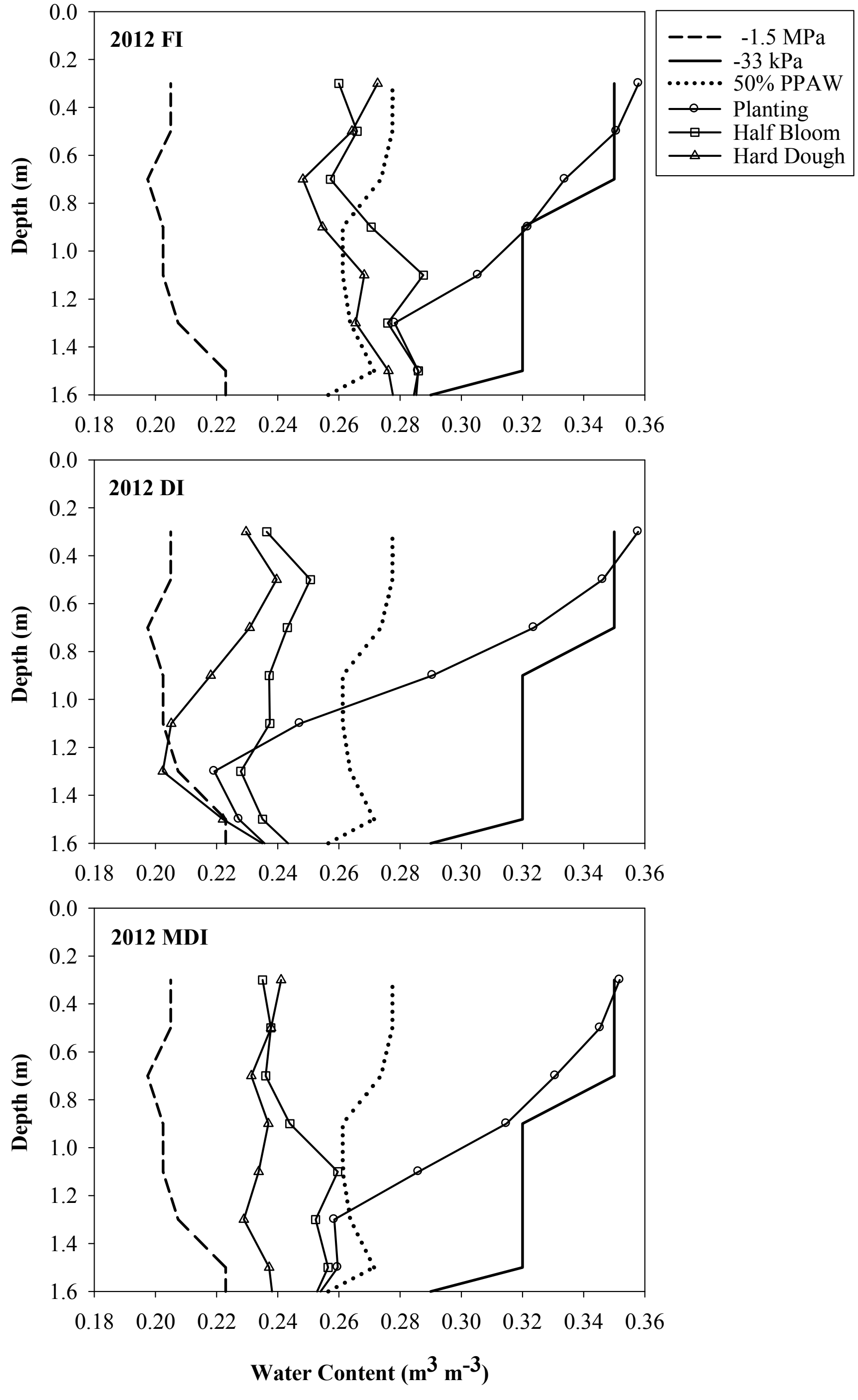

Figure 3-9. Soil water contents by depth increments in relation to water content at field capacity (-33 kPa), wilting point (-1.5 MPa) and 50% potential plant available water [50% *PPAW*(*z*)] in 2012 for full irrigation (FI), managed deficit irrigation (MDI), and deficit irrigation (DI) treatments.

III.4 SUMMARY AND CONCLUSIONS

Water use during critical growth stages was year specific due to variable precipitation and antecedent soil moisture even though irrigation strategies were maintained as planned in all years. In 2010, soil water contents under FI were greater than 50% $PPAW(z)$ from emergence through hard dough from 0- to 1.2-m. In 2011, water contents were also above 50% $PPAW(z)$ under FI throughout the growing season, but this was only from 0- to 0.6-m. While soil water contents at all depths for FI were > 50% $PPAW(z)$ at emergence in 2012, water contents above 0.8 m were < 50% $PPAW(z)$ at half-bloom.

Maximum LAI was attained during boot stage in 2012 whereas it was attained during soft dough in 2010 and 2011. In 2012, green leaf area began to decline during grain fill, which likely reduced assimilation of photosynthates for translocation into grain and thus contributed to the observed yield reduction compared with previous years. Maximum rooting depth varied among cropping year. In 2010 and 2012, maximum rooting depth was not influenced by irrigation strategy. However, in 2011, maximum rooting depth was greatest under FI. Rooting depth was deeper in 2012 compared with 2011 and 2010 as inferred from changes in soil water contents, but confirmation of this was not completed with final rooting depth measurements. It is likely that the suboptimal yields in 2012 under all irrigation treatments resulted from greater water stress as implied by lower LAI after half-bloom compared with the other years. Although stored soil water was available deeper in the profile in 2012 (> 50% $PPAW(z)$), there was likely insufficient rooting densities to fully access this water. When root length density is sparse, water contents near roots would be expected to be lower compared with large-scale, volume average water contents assessed by the neutron moisture gage. Consequently, $PPAW(z)$ assessed using the neutron moisture gage at these deeper depths in 2012 may not reflect soil water contents near the roots and hence the water status of the crop. As a result, irrigation applied based on 50% $PPAW$ in the root zone was likely insufficient to obtain maximum yield. Therefore, irrigation scheduling based on managed allowed depletion may need to be modified by weighting available water in the depth of greatest root densities (near the surface) more heavily to account for sparser root densities deeper in the profile.

Evaluation of MDI under other growing conditions, soils, and irrigation levels may be necessary to determine if this irrigation strategy has the potential for widespread application. Additionally, evaluation of management at greater fractions of full irrigation considered in this study is warranted since the maximum WUE might be attained between 75 and 100% of full irrigation.

While grain yield under FI was significantly greater each year compared with deficit irrigation strategies, under limited water, yield of MDI was significantly greater than that of DI in 2010 and 2012. Increased irrigation in 2011 mitigated significant differences between DI and MDI in that year. Therefore, on fine-textured soils with considerable soil water storage, utilization of MDI to concentrate irrigation water at the critical growth stages can potentially optimize water use and production under limited water. Alternative cropping scenarios and management regimes, such as planting fewer acres and maintaining a FI crop may prove to be the most economical depending on seasonal precipitation and stored soil water.

CHAPTER IV

CONCLUSIONS

As water supplies become limited either due to declining well capacities or regulations limiting pumping, producers are faced with the adoption of management practices that maximize yield per unit water rather than yield per unit land area. Critical management decisions that must be addressed include incorporation of drought tolerant crops, decreasing water applied, and/or decreasing irrigated acreage to accommodate full irrigation under limited well capacities. Understanding plant water use dynamics is essential to evaluate and incorporate water conservation measures into irrigation practices; however, producers will not incorporate water conservation measures that pose unacceptable production risks. Management of deficit irrigation whereby irrigation is concentrated between growing point differentiation and half-bloom was suggested as an alternative to deficit irrigation at a fraction of full irrigation as it has the potential to minimize production risks when water is limited.

IV.1 SORGHUM WUE AND GRAIN YIELD

It was hypothesized that less frequent irrigation applications, such as under managed deficit irrigation (MDI), would promote greater water use efficiency (WUE) and root elongation. There were not any differences in rooting depth between irrigation treatments in 2010 and 2012, but in 2011, greatest rooting depth was achieved under full irrigation (FI). This is likely a factor of greater plant available water (*PAW*) at lower soil depths under FI. The WUE of MDI was greater than that of deficit irrigation (DI) all years; however, this difference was only significant in 2012. The WUE of FI was significantly greater than MDI in one year with no significant differences observed in the other two years. An equivalent WUE under MDI compared with FI was likely attained because of (i) reduced soil evaporation during the vegetative stage, (ii) less water flow deeper into the profile where it is less accessible by roots, and (iii) less water use during growth stages that contribute little to yield (e.g. after hard dough). While less water is used under MDI, it was at the expense of lower yield per unit area. Grain yield under FI was greatest in all years. Grain yield of MDI was only significantly greater than that of DI in two of the three years (2010 and 2012). Grain yield was not correlated with seed mass in all study years. In contrast, grain yield was strongly correlated with the number of seeds per panicle except in 2010 for MDI and FI where maximum yield potential was realized. These results suggest that water use during growing point differentiation to anthesis was important in attaining yield potential under the conditions of this study.

IV.2 PLANT AVAILABLE WATER AND CROP WATER USE

Cumulative water use between growing point differentiation and half-bloom was significantly correlated to yield (r^2=0.94). In all years, steeper changes in surface soil water with time and steeper gradients in profile water contents were observed under deficit treatments in comparison to the FI treatment. While it was hypothesized that lower near surface soil water potentials generated under deficit irrigation would promote increased rooting depth and greater water uptake deeper in the profile, there was no evidence of compensatory uptake at deeper depths in this study. The greatest observed maximum rooting depths were under full irrigation.

In 2011, surface (0- to 0.6-m) water contents under FI were ≥ 50% $PPAW(z)$ while the remainder of the profile was < 50% $PPAW(z)$ from planting through maturity. As a result, the rooting depth and hence crop water use was restricted to near surface depths (0- to 0.6-m). While water contents below 0.6 m did not recover from initially dry conditions in 2011 under all treatments, the limited rooting depth in 2011 did not significantly influence yield compared with 2010.

In 2012 under FI, although depth averaged water contents for the entire profile (0 to 1.6 m) were greater than 50% PPAW, surface water contents (0- to 0.6-m) were < 50% $PPAW(z)$ while the remainder of the profile was > 50% $PPAW(z)$ from emergence to hard dough. Observed water stress and suboptimal yields in 2012 under FI suggest that, although stored soil water was available deeper in the profile, there was likely insufficient root density to fully access this water. Consequently, irrigation scheduling based on *PAW* evaluated within the 0 to 1.6 m root zone underestimated crop water requirements.

IV.3 MANAGEMENT IMPLICATIONS

Pre-plant soil water and the distribution of available water throughout the profile was found to be an important consideration in irrigation scheduling based on managed allowed depletion. Near maximum yield was attained even though crop water uptake was restricted to above 0.6 m and water contents deeper in the profile were less than 42% *PPAW*. In contrast, when much of the plant available water was located deeper in the profile, crop water stress and reduced yield were observed. In essence, assessment of the plant available water within the control volume should be reduced in portions of the profile where root length densities are sparse to more correctly approximate crop water status. It is also likely that the depth weighting of *PAW* and depth over which it is integrated may change in response to the soil water distribution in the profile from emergence to later in the growing season.

The results of this study and associated management implications are most applicable to fine textured soils with considerable plant available water within the profile that permits some flexibility in irrigation scheduling. While a well-managed fully irrigated crop resulted in greatest yields and equivalent or greater WUEs, management of deficit irrigation has the potential to optimize yield and WUE under limited water. Based on the results of this study, producers must have some information regarding the depth distribution of available soil water so that an appropriate management depth can be defined to correctly schedule irrigation applications based on plant available soil water. This is important not only to avoid excessive crop water stress under deficit irrigation but also to prevent irrigation at rates beyond crop requirements that undoubtedly results in reductions in WUE. There is often a narrow margin between attaining an ideal full irrigation and over irrigation where WUE begins to decline.

REFERENCES

Allen, R.G., L.S. Pereira, D. Raes, and M. Smith. 1998. Crop Evapotranspiration, FAO Irrigation and Drainage Paper No. 56, United Nations Food and Agriculture Organisation, Rome, Italy.

Allen, R.G., L.S. Pereira, D. Raes, and J.L. Wright. 2005. FAO-56 dual crop coefficient method for predicting evaporation from soil and application extensions. J. Irrig. Drain. Eng. 131(1):85-93.

Allen, R.R., and J.T. Musick. 1993. Effect of tillage and preplant irrigation on sorghum production. Applied Eng. in Agric. 6(5):611-618.

Assefa,Y., S.A. Staggenborg and V.P.V. Prasad. 2010. Grain sorghum water requirement and responses to drought stress: a review. Crop Mgmt. DOI:10.1094/CM-2010-1109-01-RV

Baumhardt, R.L. and R.J. Lascano. 1993. Physical and hydraulic properties of a calcic horizon. Soil Sci: 155:368-375.

Blum, A. 1975. Effect of the BM gene onepicuticular wax deposition and the spectral characteristics of sorghum leaves. SABRAO J. 7:45-52.

Blum, A. 2005. Drought resistance, water-use efficiency, and yield potential – are they compatible, dissonant, or mutually exclusive? Aust. J. Agric. Res. 56:1159-1168.

Blum, A. 2009. Effective use of water (EUW) and not water-use efficiency (WUE) is the target of crop yield improvement under drought stress. Field Crops Res. 112:119-123.

Böhm, W. 1979. Methods of Studying Root Systems. Ecological Studies, Springer, Berlin.

Bordovsky, J.P., J.T. Mustian, A.M. Cranmer, C.L. Emerson. 2011. Cotton-grain sorghum rotation under extreme deficit irrigation conditions. Applied Eng. in Ag. 27(3):359-371.

Calzadilla, A., K. Rehdanz, and R.S.J. Tol. 2010. The economic impact of more sustainable water use in agriculture: a computable general equilibrium analysis. J. of Hydrol. 384:292–305.

Chavez, M.M, J.P. Maroco, and J.S. Pereira. 2003. Understanding plant responses to drought-from genes to the whole plant. Funct. Plant Biol. 30:239-264.

Childs, S.W. and R.J. Hanks. 1975. Model of soil salinity effects on crop growth. Soil Sci. Soc. Am. Proc. 39:617-622.

Crauford, P.Q. and J.M. Peacock. 1993. Effect of heat and drought stress on sorghum (*Sorghum bicolor*). II. Grain Yield. Exp. Agric. 29:77-86.

Ebercon, A., A. Blum, W.R. Jordan. 1977. A rapid calorimetric method for epicuticular wax content of sorghum leaves. Crop Sci. 17:179.

Eck, H.V. and J.T. Musick. 1979. Plant water stress effects on irrigated sorghum. I. effects on yield. Crop Sci. 19:589-592.

English, M.J. 1990. Deficit irrigation. I: analytical Framework. J. Irrig. Drain. Eng. 116(3): 399–412

English, M.J., K.H. Solomon, and G.J. Hoffman. 2002. A paradigm shift in irrigation management. J. Irrig. Drain. Eng. 128(5):267-277.

Evans, R.G. and E.J. Sadler. 2008. Methods and technologies to improve efficiency of water use. Water Resour. Res. Vol. 44. doi:10.1029/2007WR006200.

Evett, S.R., R.C. Schwartz, T.A. Howell, R.L. Baumhardt, and K.S. Copeland. 2012. Can weighing lysimeter ET represent surrounding field ET well enough to test flux station measurements of daily and sub-daily ET? Adv. in Water Res. 50:79-90. http://dx.doi.org/10.1016/j.advwatres.2012.07.023 (accessed 23 January 2014)

Evett, S.R., T.A. Howell, J.L. Steiner, and J.L. Cresap. 1993. Evapotranspiration by Soil Water Balance Using TDR and Neutron Scattering. *In* Management of Irrigation and Drainage Systems. Park City, UT., July 21-23, 1993.

Evett, S.R. and J.L. Steiner. 1995. Precision of neutron scattering and capacitance type soil water content gages from field calibration. Soil Sci. Soc. Am. J. 59:961-968.

Fereres, E. and M.A. Soriano. 2007. Deficit irrigation for reducing agricultural water use. J. Exp. Bot. 58:147-159.

Gardner, W.R. 1964. Relation of root distribution to water uptake and availability. Agron. J. 56:41-45.

Garces-Restrepo, C. D. Vermillion, G. Munoz. 2007. Irrigation management transfer. FAO Water Report Publication 32. FAO, Rome.

Garrity, D.P., D.G. Watts, C.Y. Sullivan and J.R. Gilley. 1982. Moisture deficits and grain sorghum performance: effect of genotype and limited irrigation strategy. Agron. J. 74:808-814.

Gee, G. W. and J. W. Bauder. 1986. Particle-size analysis. pp 383-411. In A. Klute (ed.). Methods of Soil Analysis. Part 1. 2nd ed. Agron. Monogr. 9. ASA and SSSA, Madison, WI.

Gerik, T., B. Bean, and R. Vanderlip. 2003. Sorghum growth and development. Texas Copperative and Extension Publication. B-6137 http://publications.tamu.edu/CORN_SORGHUM/PUB_Sorghum%20Growth%20and%20Development.pdf (accessed 9 February 2014)

Gurdak, J.J., and C.D. Roe. 2009. Recharge rates and chemistry beneath playas of the High Plains aquifer. A literature review and synthesis: U.S. Geological Survey Circular 1333.

Gurian-Sherman, D. 2012. High and Dry: Why Genetic Engineering Is Not Solving Agriculture's Drought Problem in a Thirsty World. Union of Concerned Scientists, Cambridge, MA, USA. Available at: http://www.ucsusa.org/assets/documents/food_and_agriculture/high-and-dry-report.pdf (accessed 23 January 2014)

Hatfield, J.L., T.J. Sauer, J.H. Prueger. 2001. Managing soils to achieve greater water use efficiency: a review. Agron. J. 93:271-280.

Howell, T.A. and E.A. Hiller. 1975. Optimization of water use efficiency under high frequency irrigation I. Evapotranspiration and yield relationship. Trans. ASAE. 18: 873-878.

Howell, T.A. 2006. Challenges in increasing water use efficiency in irrigated agriculture. *In* International Symposium on Water and Land Management for Sustainable Irrigated Agriculture. Adana, Turkey, April, 2006.

Howell, T.A., J.A. Tolk, S.R. Evett, K.S. Copeland, and D.A Dusek. 2007. Evapotranspiration of deficit irrigated sorghum and winter wheat. *In* Clemmens, A.J., editor. USCID Fourth International Conference on Irrigation and Drainage. The Role of Irrigation and Drainage in a Sustainable Future, Sacramento, California, October 3-6, 2007.

Hsiao, T.C. and E. Acevedo. 1974. Plant responses to water deficits, water use efficiency, and drought resistance. Agric. Meteor. 14:59-84.

Hsiao, T.C., E. Acevedo, E. Fereres and D.W. Henderson. 1976. Water stress, growth, and osmotic adjustment. Phil. Trans. R. Soc. Lond. 273:479-500. DOI: 10.1098/rstb.1976.0026

Jones, D.L. and F. Gaines. 1941. Pump irrigation on the South Plains. Texas Agric. Exp. Stn. Prog. Rep. 728.

Jones, O.R. and G.L. Johnson. 1991. Row width and plant density effects on Texas High Plains sorghum. J. Prod. Agric. 4:613–621.

Klepper, B., H.M. Taylor, M.G. Huck, and E.L. Fiscus. 1973. Water relations and growth of cotton in drying soil. Agron. J. 65:307-310.

Klute, A. 1986. Water retention: Laboratory methods. p. 635–662. *In* A. Klute (ed.). Methods of soil analysis. Part 1. 2nd ed. Agron. Monogr. 9. ASA and SSSA, Madison, WI.

Klocke, N.L., R.S. Currie, D.J. Tomsicek and J.W. Koehn. 2012. Sorghum yield response to deficit irrigation. Trans. of the ASABE. 55(3):947-955.

Kramer, P.J. and T.S. Coile. 1940. An estimation of the volume of water made available by root extension. Plant Phys. 15:743-747.

Lafarge, T.A. and G.L. Hammer. 2002. Tillering in grain sorghum over a wide range of population densities modeling dynamics of tiller fertility. Ann. Bot. 90:99-110.

Mayaki, W.C., L.R. Stone, and I.D. Teare. 1976. Irrigated and nonirrigated soybean, corn and grain sorghum root systems. Agro. J. 68:532-534.

McWilliams, D. 2003. Drought strategies for corn and grain sorghum. Coop Ext. Circ. 580, New Mexico State Univ., Las Cruces, NM.

Monteith, J.L. 1986. How do crops manipulate water supply and demand? Phil. Trans. R. Soc. Lond. 316: 245-259.

Moroke, T.S. 2002. Root distribution, water extraction, patterns, and crop water use efficiency of selected dryland crops under differing tillage systems. Ph.D. diss. Texas A&M Univ. College Station, TX.

Moroke, T.S., R.C. Schwartz, K.W. Brown, and A.S.R. Juo. 2005. Soil water depletion and root distribution of three dryland crops. Soil Sci. Soc. Am. J. 69:197-205.

Musick, J.T., and F.R. Lamm. 1990. Preplant irrigation on the Central and Southern High Plains: A review. Trans ASABE. 33(6)1834-1842.

Musick, J.T., and W.H. Sletten. 1966. Grain sorghum irrigation-water management on Richfield and Pullman Soils. Trans. ASAE. 9:369-373.

New, L. 2004. Grain Sorghum Irrigation. Texas Agri-Life Bulletin. B-6152.

Ober, E.S., and R.E. Sharp. 2007. Regulation of root growth responses to water deficit. *In* Advances in Molecular Breeding toward Drought and Salt Tolerant Crops. editors M.A. Jenks, P.M. Hasegawa, and S.M. Jain. pp. 33–53.

Ockerby, W.E., D.J. Midmore, D.F. Yule. 2001. Leaf modification delays panicle initiation and anthesis in grain sorghum. Aust. J. Agric. Res. 52:127-135.

Maman, N., S.C. Mason, D.J. Lyon, and P. Dhungana. 2004. Yield components of pearl millet and grain sorghum across environments in the central Great Plains. Crop Sci. 44: 2138-2145.

Peacock, J.M. 1982. Response and tolerance of sorghum to temperature stress. *In* Sorghum in the Eighties: Proceedings of the International Symposium on Sorghum. Patancheru, A.P. India, November 2-7, 1981.

Peacock, J. M. and G. M. Heinrich. 1984. Light and temperature responses in sorghum. *In* Agrometeorology of Sorghum and Millet in the Semi-Arid Tropics: Proceedings of the International Symposium on Sorghum. Pantancheru, India. November 15-20, 1982. ICRISAT

Prasad, P.V.V., S.R. Pisipati, R.N. Mutava and M.R. Tuinstra. 2008. Sensitivity of grain sorghum to high temperature stress during reproductive development. Crop Sci. 48:1911-1917.

Rhoades, J.D. 1997. Sustainability of irrigation: An overview of salinity problems and control strategies. pp. 1-42. *In* CWRA 1997 Annual Conf. Footprints of Humanity: Reflections on Fifty Years of Water Resource Developments. Lethbridge, Alberta, Canada, June 3-6, 1997.

SAS Institute. 2004. User's guide: Statistics. SAS Inst., Cary, NC.

Santamaria, J.M., M.M. Ludlow, and S. Fukai. 1990. Contribution of osmotic adjustment to grain yield in Sorghum bicolor (L.) Moench under water-limited conditions. I. water stress before anthesis. Aust. J. Agric. Res. 41:51-65.

Sharp, R.E., Y. Wu, G.S. Voetberg, I.N. Saab, and M.E. LeNoble. 1994. Confirmation that abscisic acid accumulation is required for maize primary root elongation at low water potentials. J. Exp. Bot. 45:1743-1751.

Staggenborg, S.A., K.C. Dhuyvetter, and W.B. Gordon. 2008. Grain sorghum and corn comparisons: Yield, economoic and environmantal responses. Agron. J. 100:1600-1604.

Tolk, J.A., T.A. Howell, and S.R. Evett. 1995. Grain sorghum growth, water use and yield in contrasting soils. Agric. Water Manage. 35:29-42.

Tolk, J.A., T.A. Howell and F.R. Miller. 2013. Yield component analysis of grain sorghum grown under water stress. Field Crops Res. 145:44-51.

US Geological Survey. 2013. National Water Quality Assessment Program: High Plains Regional Groundwater Study. Located at: http://co.water.usgs.gov/nawqa/hpgw/HPGW_home.html (accessed 23 January 2014)

US Geological Survey. 2008 High Plains RegionalGround-Water Study. Located at: http://co.water.usgs.gov/nawqa/ hpgw/factsheets/DENNEHYFS1 (accessed 23 January 2014)

Vadez, V., J. Kholova, R.S. Yadav and C.T. Hash. 2013. Small temporal differences in water uptake among varieties of pearl millet (Pennisetum glaucum (L.) R. Br.) are critical for grain yield under terminal drought. Plant Soil 371:447-462. DOI 10.1007/s11104-013-1706-0

Van Oosterom, E.J. and G.L. Hammer. 2008. Determination of grain number in sorghum. Field Crops Res. 108:259-268.

Vrugt, J.A., J.W. Hopmans, and J. Šimunek. 2001. Calibration of a two-dimensional root water uptake model. Soil Sci. Soc. Am. J. 65:1027-1037.

Wagner, K. 2012. Status and trends of irrigated agriculture in Texas. Texas Water Resources Institute Report. TWRI EM-115

APPENDIX A

NEUTRON MOISTURE GAGE CALIBRATION COEFFICIENTS

Table A-1. Neutron moisture gage calibration coefficients for the Ap, Bt, and Btk horizons of the Pullman soil.

Horizon	Depth Increment	Intercept	slope	RMSE
	----m----			
Ap	0-0.10	0.009	0.228	0.003
Bt	0.30-1.10	-0.095	0.260	0.008
Btk	1.30-2.30	-0.034	0.213	0.007

APPENDIX B

SOIL PARTICLE SIZE ANALYSIS OF THE PULLMAN SOIL

Soils of the Pullman soil series (Fine, mixed, superactive, thermic Torrertic Paleustolls) are slowly permeable, deep soils that formed in calcareous, loamy and clayey sediments. While the Ap horizon of Pullman soils are classified as clay loam, because of deep tillage, mixing with the Bt horizon below 0.20 m has resulted in elevated clay contents in the 0- to 0.20- m depth increment. The Bt transitions to a calcic B (Btk) at 1.4 m distinguished by up to 50 calcium carbonates (Tolk et al., 1995). In the Pullman soils, the depth to the calcic horizon can range between 0.5 to 1.5 m (Tolk et al., 1995).

Table B-1. Percent silt and clay for the Pullman soil determined by from hydrometer based particle size analysis.

Depth (m)	Horizon	%Silt	%Clay	Texture (USDA)
0-0.05	Ap	37.5	47.9	C
0.05-0.10	Ap	38.0	49.0	C
0.10-0.15	Ap	36.1	51.6	C
0.15-0.20	Ap	37.1	52.7	C
0.20-0.30	Bt1	37.3	51.4	C
0.30-0.40	Bt1	38.6	51.1	C
0.40-0.60	Bt2	37.0	51.6	C
0.60-0.80	Bt2	37.9	49.5	C
0.80-1.00	Bt2	37.5	46.7	C
1.00-1.20	Bt2	36.3	45.9	C
1.20-1.70	Btk	39.0	45.6	C

APPENDIX C

SOIL WATER RENTENTION CHARACTERISTICS OF THE PULLMAN SOIL

Table C-1. Soil water retention measurements (matric potential and volumetric water contents) for the Pullman soil at 0.05 to 2.0 m depth increments.

Depth	Tension	Mean θ	Stdev
m	MPa	----- m^3	m^{-3} -----
0.05	0.010	0.504	0.016
0.05	0.032	0.322	0.008
0.05	0.048	0.306	0.010
0.05	0.100	0.279	0.009
0.05	0.497	0.226	0.004
0.05	1.497	0.214	0.002
0.10	0.010	0.504	0.008
0.10	0.032	0.320	0.009
0.10	0.048	0.308	0.012
0.10	0.100	0.280	0.008
0.10	0.497	0.225	0.005
0.10	1.497	0.203	0.000
0.15	0.010	0.469	0.012
0.15	0.029	0.370	0.002
0.15	0.046	0.358	0.003
0.15	0.100	0.342	0.003
0.15	0.497	0.279	0.011
0.15	1.497	0.228	0.021
0.20	0.010	0.475	0.014
0.20	0.029	0.391	0.018
0.20	0.046	0.379	0.019
0.20	0.100	0.357	0.020
0.20	0.497	0.290	0.024
0.20	1.497	0.242	0.001

Table C-1 cont.

Depth	Tension	Mean θ	Stdev
m	MPa	----- m^3 m^{-3} -----	
0.40	0.012	0.350	0.026
0.40	0.028	0.312	0.005
0.40	0.050	0.291	0.002
0.40	0.098	0.277	0.001
0.40	0.248	0.271	0.003
0.40	0.459	0.251	0.001
0.40	1.497	0.239	0.012
0.60	0.012	0.330	0.017
0.60	0.028	0.309	0.015
0.60	0.050	0.286	0.016
0.60	0.098	0.267	0.008
0.60	0.248	0.262	0.007
0.60	0.459	0.247	0.006
0.60	1.497	0.216	0.002
0.80	0.012	0.337	0.013
0.80	0.030	0.310	0.006
0.80	0.050	0.296	0.008
0.80	0.099	0.279	0.013
0.80	0.248	0.264	0.004
0.80	0.459	0.240	0.007
0.80	1.497	0.206	0.001
1.00	0.012	0.338	0.009
1.00	0.030	0.308	0.008
1.00	0.050	0.290	0.007
1.00	0.100	0.274	0.006
1.00	0.248	0.255	0.005
1.00	0.459	0.231	0.004
1.00	1.497	0.210	0.020

Table C-1 cont.

Depth	Tension	Mean θ	Stdev
m	MPa	------ m^3 m^{-3} -----	
1.20	0.010	0.424	0.005
1.20	0.030	0.389	0.004
1.20	0.050	0.376	0.004
1.20	0.096	0.341	0.005
1.20	0.331	0.317	0.005
1.20	0.483	0.294	0.003
1.20	1.497	0.197	0.000
1.40	0.010	0.410	0.016
1.40	0.030	0.364	0.015
1.40	0.050	0.348	0.012
1.40	0.096	0.315	0.007
1.40	0.331	0.271	0.017
1.40	0.483	0.246	0.018
1.40	1.517	0.227	0.010
1.70	0.010	0.380	0.023
1.70	0.028	0.351	0.005
1.70	0.049	0.334	0.005
1.70	0.101	0.309	0.006
1.70	0.331	0.243	0.005
1.70	0.483	0.220	0.005
1.70	1.517	0.182	0.001
2.00	0.010	0.395	0.012
2.00	0.028	0.363	0.011
2.00	0.049	0.341	0.011
2.00	0.101	0.310	0.013
2.00	0.331	0.248	0.012
2.00	0.483	0.224	0.013
2.00	1.517	0.175	0.002

APPENDIX D

CORRELATION OF YIELD TO SEED PANICLE^{-1} AND SEED MASS

Table D-1: Pearson's correlation coefficient and associated probabilities, *p*, reflecting the correlation between yield and seed panicle^{-1}.

Year	IS	Pearson's r	*p*
2010	DI	0.827	0.006
2010	FI	0.423	0.257
2010	MDI	-0.014	0.972
2011	DI	0.942	< 0.001
2011	FI	0.899	0.001
2011	MDI	0.727	0.027
2012	DI	0.964	< 0.001
2012	FI	0.979	< 0.001
2012	MDI	0.874	0.002

Table D-2: Pearson's correlation coefficient and associated probabilities, *p*, reflecting the correlation between yield and seed mass.

Year	IS	Pearson's r	*p*
2010	DI	0.492	0.178
2010	FI	0.641	0.063
2010	MDI	0.408	0.275
2011	DI	-0.774	0.014
2011	FI	-0.585	0.097
2011	MDI	0.366	0.333
2012	DI	0.112	0.775
2012	FI	-0.614	0.079
2012	MDI	-0.153	0.694